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# Modeling crop response to nitrogen

by

Nanchang Yang

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirement for the degree of

DOCTOR OF PHILOSOPHY

Major: Soil Science (Soil Fertility)

Major Professor: Alfred M. Blackmer

Iowa State University

Ames, Iowa

1999

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# GENERAL INTRODUCTION

The methodology used for selecting rates of N fertilization during corn production is important because N fertilizers are both essential and expensive. Applying too little N reduces yields and profits for producers. Applying too much N reduces profits for producers and causes unnecessary environmental degradation.

Models of yield response to fertilizer N have been the basic tool used to select optimal rates of N fertilization. These models, however, carry the disadvantage of not considering amounts of plant-available N in the soil before fertilizers are applied. This is a major problem in modern agricultural systems because soils are maintained with relatively high levels of plant-available N. With high levels of plant-available N, yield responses often are not observed.

Recent advances in soil and tissue testing offer a new approach to modeling crop responses to nitrogen. The late-spring test for soil nitrate can be used to estimate amounts of plant–available N in the soil just as corn crops begin rapid growth. The end-of-season test for cornstalk nitrate can be used to measure the sufficiency (i.e., supply relative to needs) of N for crop growth. The overall objective of this study is to explore the potential benefits of using relationships between soil and stalk nitrate concentrations to model responses of corn to fertilizer N.

## Dissertation Organization

This dissertation is presented as a series of three papers intended for publication. All three papers will be submitted to Agronomy Journal. The papers are preceded by a General Introduction and succeeded by a General Conclusion.

# DEVELOPMENT OF YB INDEX OF NITROGEN SUFFICIENCY IN CORN

A paper to be submitted to the Agronomy Journal

N. C. Yang and A. M. Blackmer

Abstract

Site-specific assessments of N sufficiency for corn production can be obtained by measuring soil nitrate concentrations in late spring and by measuring stalk nitrate concentrations at the end of the season. Although both the soil and tissue tests have been widely studied, relationships between results of the two tests have received little attention. Relationships between results of these tests were studied by using data collected in 70 response trials having at least 6 rates of N applied. Results showed that nonlinear relationships between soil and stalk nitrate concentrations were a problem, especially in studies where only a few rates of N were applied. This problem was addressed by developing an index of stalk nitrate concentrations, YB index, that tends to be linearly related to soil nitrate concentrations. This index is calculated by the formula -100 Log(Log(14000/StalkN)) + 11.4, where StalkN denotes concentrations of stalk nitrate in mg N/kg. Results indicated that relationships based on YB index values described plant responses to fertilizer at least as well as commonly used relationships based on yields. Relationships based on the YB index values offer the advantage that responses to N can be measured even with rates of N applied at near- and above-optimal rates.

## Introduction

Nitrate concentrations in lower cornstalks at the end of the season provide the basis for a tissue test that characterizes N sufficiency for corn growth (Binford et al. 1990, 1992a). This tissue test was calibrated by establishing relationships between stalk nitrate concentrations and relative yields (yields expressed as percentages of the highest yield attained by addition of N under otherwise similar conditions). Pooled data from many N-response trials showed that stalk nitrate concentrations less than 250 mg N/kg are indicative of yield-limiting deficiencies of N and that concentrations greater than about 700 mg N/kg are indicative of sufficient N to maximize yields. A key feature of the test is that it can characterize degrees of N excess as well as degrees of N deficiency. High rates of N application often produce stalk nitrate concentrations >10,000 mg N/kg.

Studies to calibrate this tissue test showed nonlinear relationships between rates of N application and stalk nitrate concentrations. Binford et al. (1990, 1992a) described this relationship by using a discontinuous model consisting of two linear segments. The first segment described situations where additions of N resulted in increases in dry matter production without increases in stalk nitrate concentration, the second segment described situations in which added N increased stalk nitrate concentrations and had little or no effect on yields. Nonlinearity occurs because the effect of any given addition of fertilizer N on stalk nitrate concentrations is much smaller if the added N does not result in above-optimal supplies of N than if it does. The problem of nonlinearity seems unavoidable when stalk nitrate concentrations are related to rates of fertilizer application because unknown amounts of N usually are supplied by sources other than the fertilizer.

Concentrations of nitrate in the surface 30-cm layer of soil when plants are 15 to 30 cm tall provide an index of N availability to corn that includes N from sources other than the fertilizer applied (Magdoff et al., 1984; Blackmer et al., 1989, 1991; Fox et al., 1989; Magdoff et al., 1990; Binford et al., 1992a; Bundy and Meissinger, 1994). Bundy and Meissinger (1994) noted that studies conducted under a surprisingly wide range of conditions have shown that optimal soil nitrate concentrations are in the range of 20 to 25 mg N/kg. It is reasonable to expect, therefore, that soil nitrate concentrations in this range should have a tendency to result in cornstalk nitrate concentrations that are near optimal.

Here we describe studies of the relationships between concentrations of soil nitrate in late spring and concentrations of nitrate in cornstalks at the end of the season in trials where at least six rates of N were applied shortly before planting. The specific objective is to learn how relationships between these indexes of N availability in soil and of N sufficiency in plants can be described in efforts to make fertilizer recommendations from data collected across many trials. It is reasoned that better methods for identifying and describing trends among trials are needed to develop recommendations that address important differences among sites.

## Materials and Methods

Data were taken from a total of 1813 plots from 70 N-response trials conducted in Iowa over a period of six years (1986 - 1991). For the purpose of this paper, a trial means application of N at several rates at one site at one time by using one method of application. Most of the response trials are described by Davis (1992), Binford et al. (1992b), and Meese (1993). Each trial involved application of at least six rates of N to replicated and randomized plots before corn was planted. Fertilizer N was applied in the form of urea, ammonium sulfate, ammonium nitrate or anhydrous ammonia either in late fall of the previous year or in the spring shortly before planting. Preceding crops were either corn or soybean.

Measurements taken from each trial included concentrations of nitrate in the surface 30-cm layer of soil when corn plants were 15 to 30 cm tall and concentrations of nitrate in the cornstalks in the lower portion of cornstalks one to three weeks after black layers had formed on most kernels. Soil samples were composites of at least 8 cores taken from each plot. Stalk samples consisted of 15 twenty-cm stalk segments cut between 15 to 35 cm above the ground. Soil and stalk samples were air-dried and ground. Nitrate concentrations in the soil and stalk samples were determined by either automated colorimetric procedures or by ion selective electrodes and expressed on the basis of dry soil or stalks.

An index of N sufficiency in cornstalks was developed by pooling data from all sites, relating spring soil nitrate concentrations to the logarithm of concentrations of nitrate in the cornstalks collected at the end of the season, fitting a curve to describe this relationship, and linearizing this curve. The index was evaluated by considering its ability to produce linear relationships between spring soil nitrate concentrations to the cornstalk nitrate concentrations in individual trials.

Individual trials are numbered in order of decreasing $r^2$ values for relationship between rates of N application and yields as described by the quadratic response and plateau model, which is described by Cerrato and Blackmer (1990). This method, therefore, ranks the trials in order of decreasing quality if it is assumed there should be a functional relationship between rates of N application and yields in trials.

Analysis of variance, linear regression, and segmented model regression analysis (Waugh et al., 1973) were performed using ANOVA, GLM, and NLIN procedures of the SAS systems for windows, version 6.12 (SAS Institute, 1989).

## Results

*Problem Identification:*

Data presented in Fig. 1 indicate that relationships between spring soil nitrate concentrations and fall stalk nitrate concentrations are not linear. The relationships have two phases analogous to those described by Binford et al. (1990, 1992a), who studied

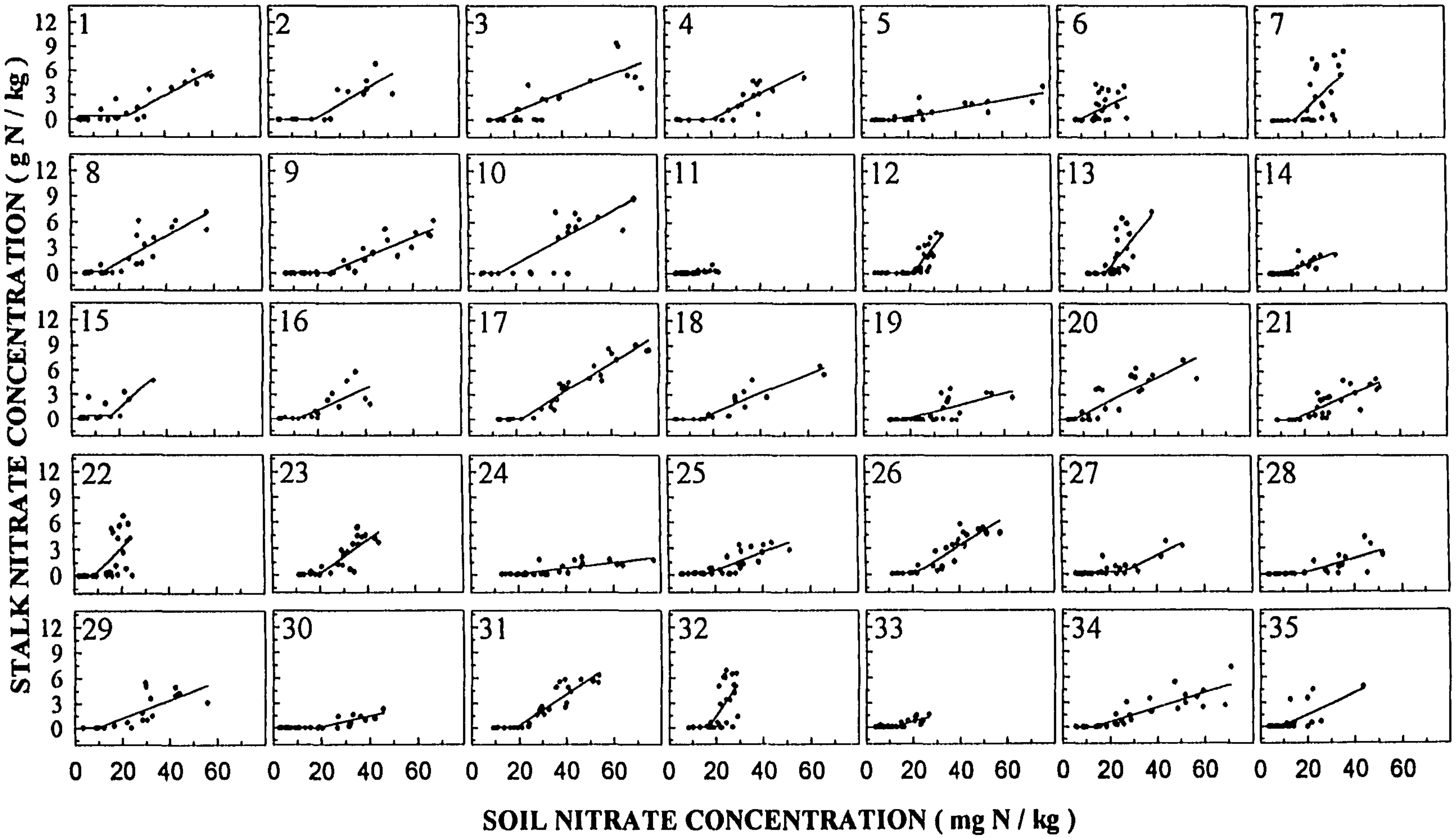



Figure 1. Within-trial relationships between end-of-season stalk nitrate concentrations and concentrations of soil nitrate measured in late spring in 70 response trials where fertilizer N was applied in early spring.

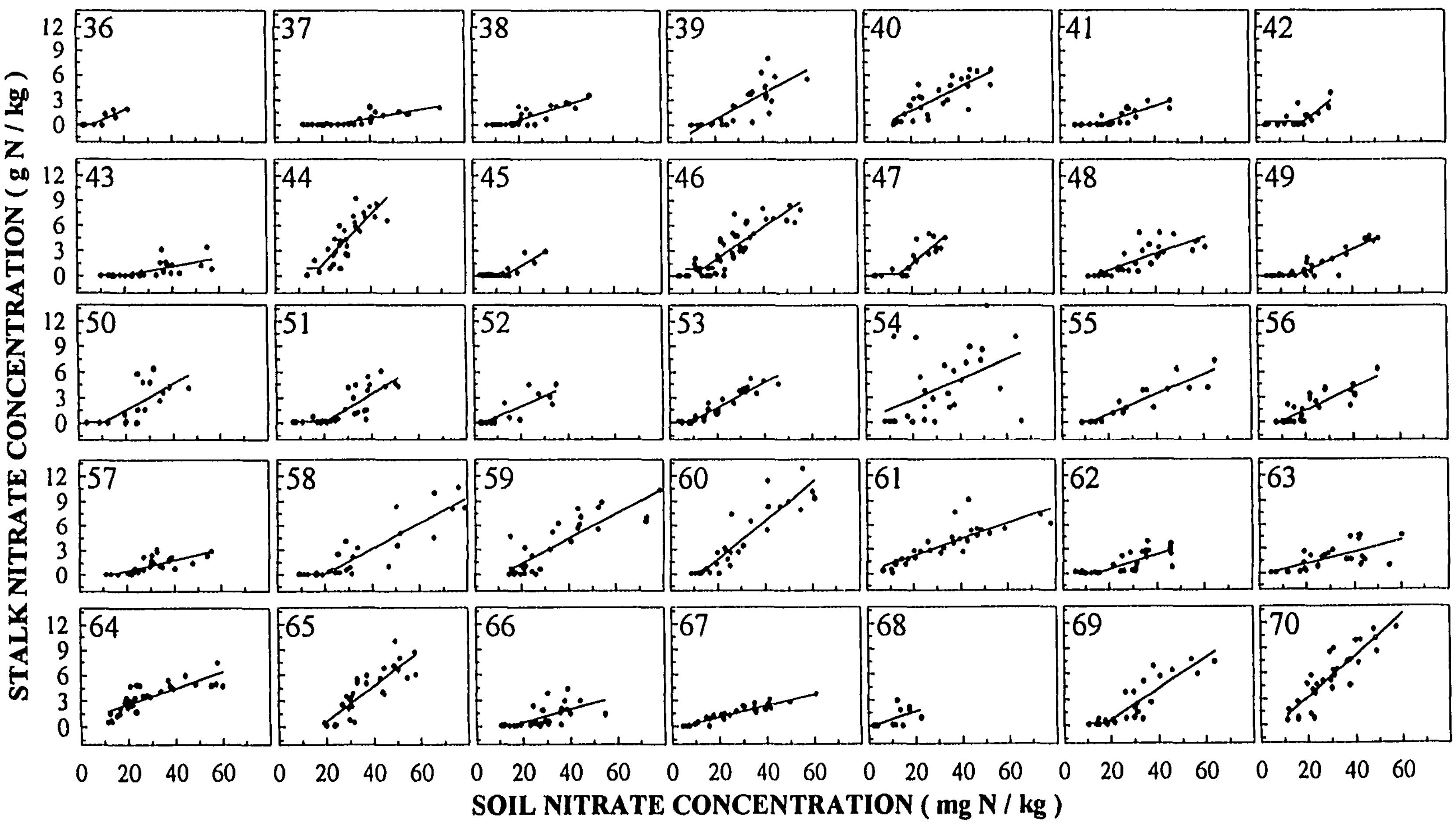



Figure 1. Continued.

relationships between rates of N application and cornstalk nitrate concentrations. The relationships in Fig. 1 should not be confused with those reported by Binford et al., (1990, 1992a) because the soil test measures nitrate from sources besides the fertilizer. Moreover, some fertilizer N may have been lost from the soil or moved below the depth sampled.

Pooled data from all sites showed a statistically significant (99% level of confidence) linear relationship between soil nitrate concentrations in late spring and stalk nitrate concentrations at the end of the season (Fig.2). This relationship accounted for 47% of the observed variability in stalk nitrate concentrations. One noteworthy problem, however, is that visual analysis of trends in stalk nitrate concentrations near the optimal range (0.7 to 2 g N/kg) is complicated by lack of separation from lower concentrations. For example, all observations below the optimal category (65% of the total) are concentrated into the bottom 5% of the figure.

Another noteworthy problem is that this presentation of data gives great emphasis to concentrations in the above-optimal range. Although effects of above- and below-optimal rates of N fertilization are important when analyzing data from N response trials, these data should not be allowed to obscure or overwhelm effects observed at near-optimal rates. Both of these problems are only the symptoms of the greater problem that considerable information is lost when nonlinear relationships of the type shown in Fig. 1 are pooled.

*Index Development:*

Relating spring soil nitrate concentrations to the logarithm of end-of-season stalk nitrate concentrations gives more emphasis to stalk nitrate concentrations that are near or below optimal (Fig. 3). This relationship can be described by equation 1,

$$\mathrm{Log(StalkN)} = \mathrm{Log}(14000) - 10^{(-0.017 * \mathrm{SoilN} + 0.069)} \qquad r^2 = 0.57 \quad (1)$$

where StalkN denotes stalk nitrate concentration (mg N/kg), SoilN denotes soil nitrate

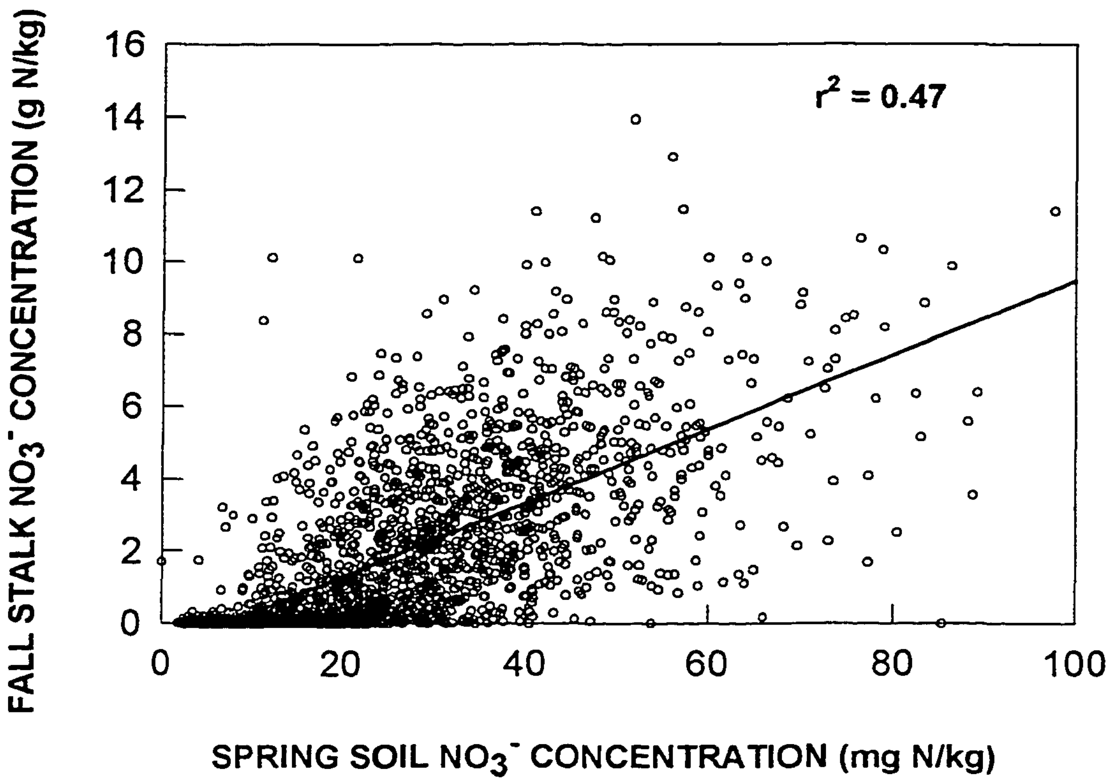



Fig. 2. Pooled relationship between end-of-season stalk nitrate concentrations and soil nitrate concentrations measured in late spring in 70 response trials where fertilizer N was applied in early spring.

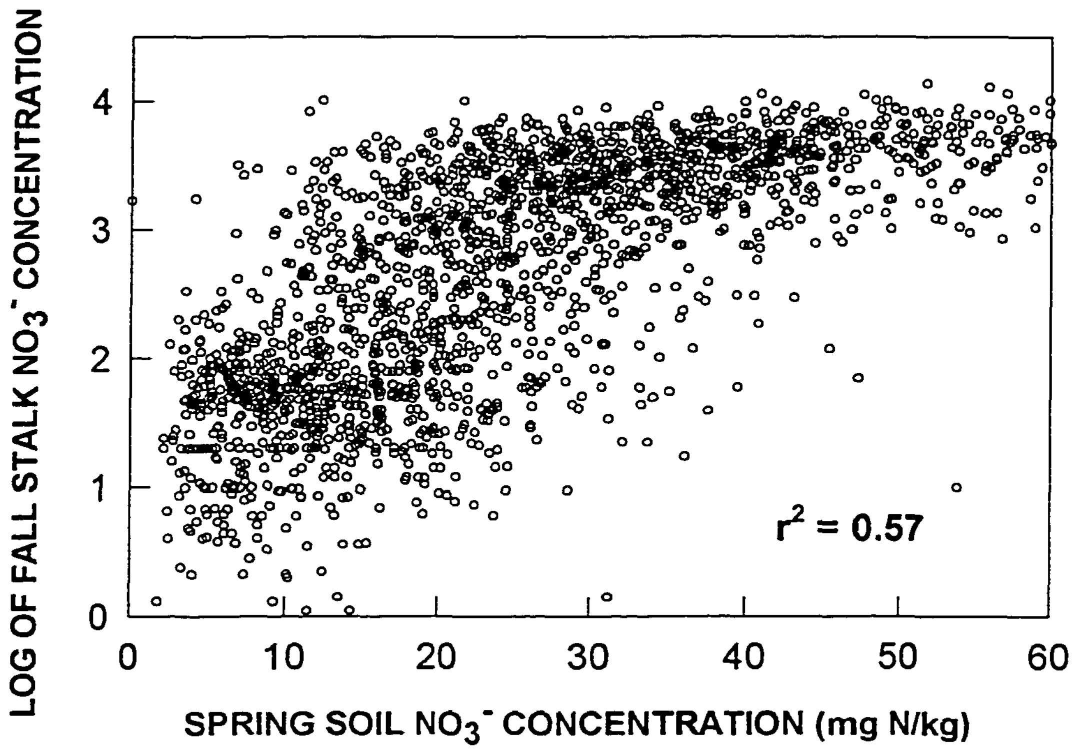



Fig. 3. Pooled relationship between logarithms of end-of-season stalk nitrate concentrations and soil nitrate concentrations measured in late spring in 70 response trials where fertilizer N was applied in early spring.

concentration (mg N/kg), the constant 14000 indicates the maximum StalkN considered useful, and –0.017 and 0.069 are constants obtained during curve fitting. Although this relationship accounts for more variability than does the linear model in Fig. 1, stalk nitrate concentrations in the above-optimal range are not linearly related to soil nitrate concentrations.

Equation (1) is linearized by equation (2),

$$- \mathrm{Log}(\mathrm{Log}(14000/\mathrm{StalkN})) = 0.017 * \mathrm{SoilN} - 0.069 \qquad (2)$$

and the left side of this equation offers an index of stalk nitrate concentration that is linearly related to soil nitrate concentrations. The index is a measure of N sufficiency (N supply expressed relative to needs) in the crop because it varies only with stalk nitrate concentration. This index has a value of zero when stalk nitrate concentration is 1400 mg N/kg.

An index of N sufficiency would be easier to use if the critical concentration of stalk nitrate were assigned an index value of zero. This would give negative values to the concentrations below the critical concentration and positive values to concentrations above the critical concentration. A concentration of 700 mg N/kg is used to divide the marginal and optimal categories in current guidelines for interpreting this test (Blackmer and Mallarino, 1996) and, therefore, could be considered a critical concentration. Adding 0.114 to both sides of Equation 2 makes the left side of the equation equal to value of zero when the stalk nitrate concentrations are 700 mg N/kg. Multiplying both sides of Equation 2 by 100 avoids the need to use decimals when using index values. The result is equation (3),

$$-100\ \mathrm{Log}(\mathrm{Log}(14000/\mathrm{StalkN})) + 11.4 = 1.7 * \mathrm{SoilN} + 4.5 \qquad (3)$$

the left side of which we denote as the YB (after Yang and Blackmer) index of N sufficiency. This index can be used only for cornstalk concentrations of 14,000 mg N/kg or less because the index is not mathematically defined at higher stalk nitrate concentrations. This limitation does not significantly diminish the practical value of the index because stalk nitrate concentrations above 14000 mg N/kg rarely occur and need to be interpreted with caution.

Figure 4 shows the relationship between YB index values and soil nitrate concentrations across all plots. The extent to which YB index values deviate from zero indicates the degree of N deficiency or excess on a scale that is linearly related to average amounts of nitrate measured in the trials included in this study. Linearity, of course, means that the change in quantity of soil N needed to produce a unit change in index value does not change with nitrate concentration in the soil or stalk.

*Index Evaluation:*

Although data pooled from many sites provides a reasonable basis for developing an index that aids in interpretation of cornstalk nitrate concentrations, there is no *a priori* reason to expect a relationship having high predictability when data from many different sites are pooled. Indeed, predictability should be limited by normally expected variability among sites. Such variability could include errors caused by not sampling the entire depth of the root zone, by losses or mineralization of N after the soils were tested, and by differences in N requirements among hybrids. Each of these factors varies independently in response to complex interactions of soil properties, weather conditions, plant genetics, and other site-specific conditions. Because all of these factors remain constant within a single trial, evaluations of the index should begin with data collected within individual trials.

Figure 5 shows relationships between soil nitrate concentrations and YB index values for each of the seventy trials included in the study. Analysis showed that the $r^2$ values for these relationships ranged from 0.32 to 0.87 and had a mean of 0.66 and a standard deviation of 0.13. The $r^2$ values for the segmented models shown in Fig. 1 ranged from 0.23 to 0.90 with a mean

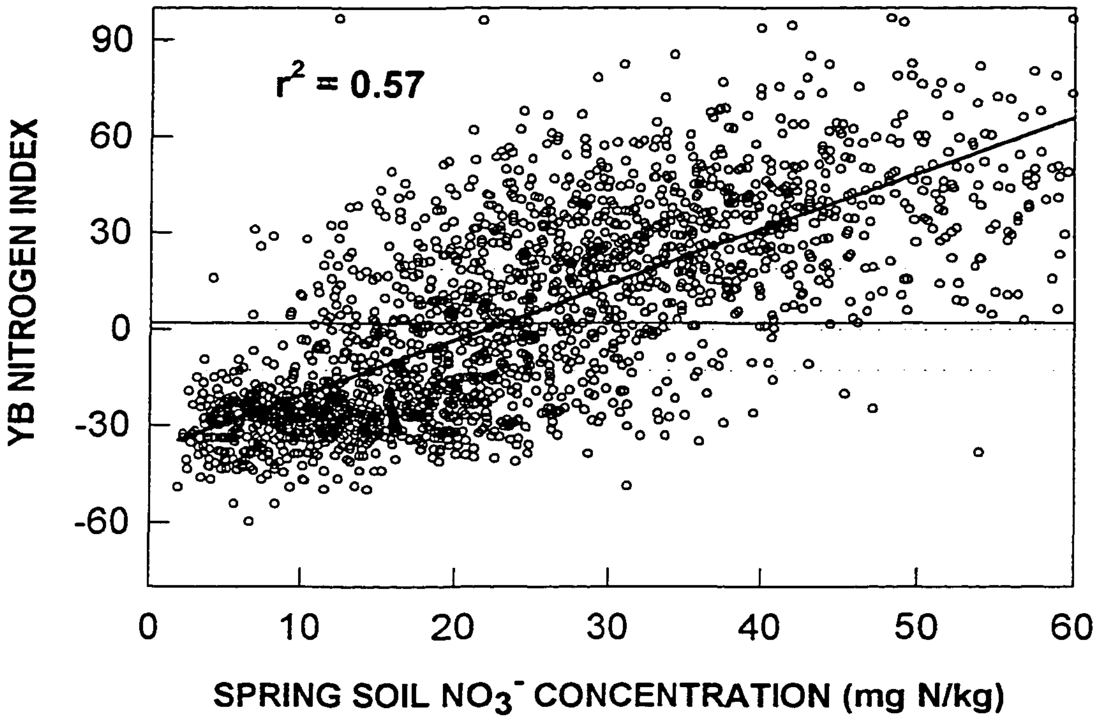



Fig. 4. Pooled relationship between YB index values and soil nitrate concentrations measured in late spring in 70 response trials where fertilizer N was applied in early spring.

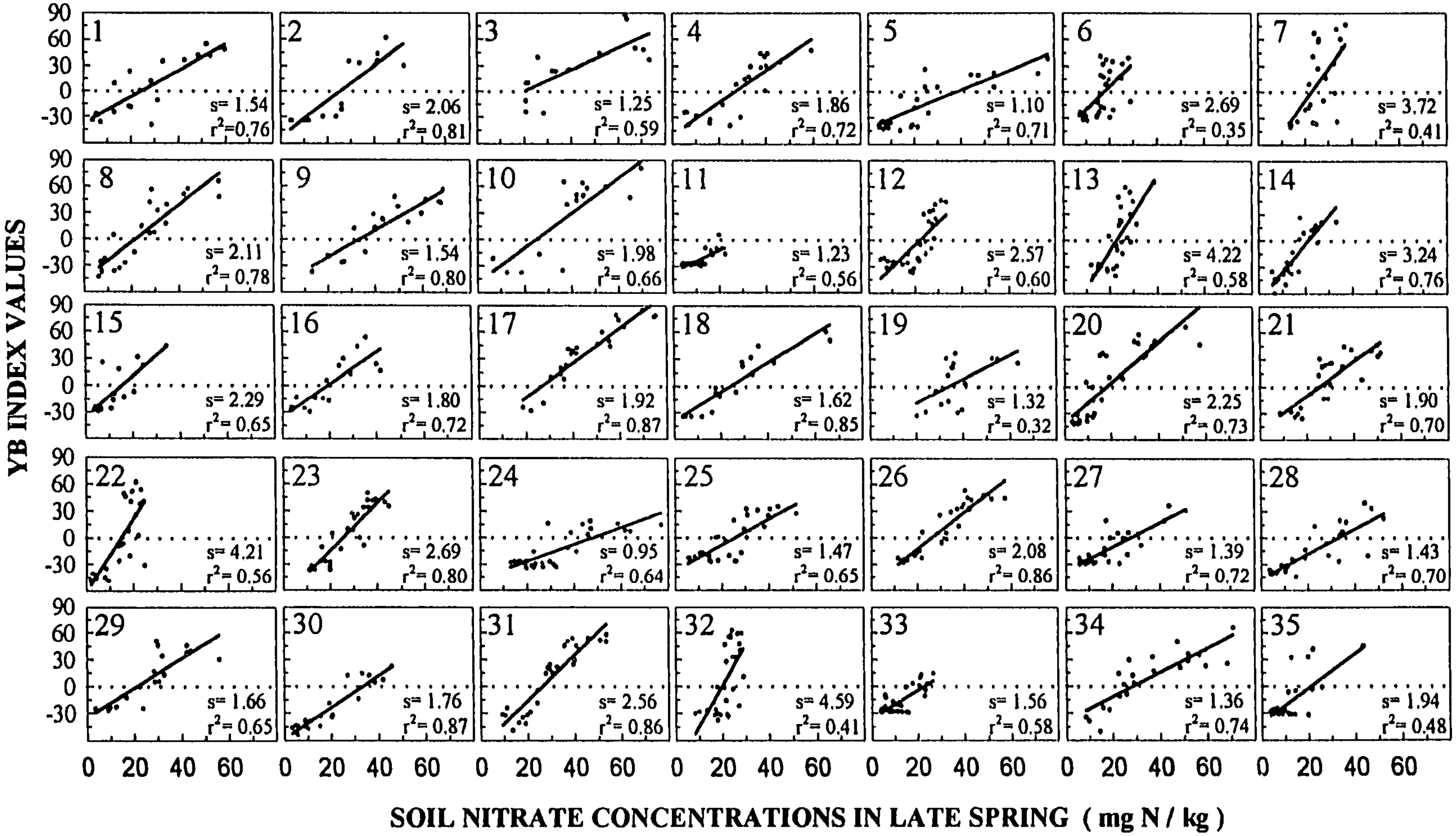
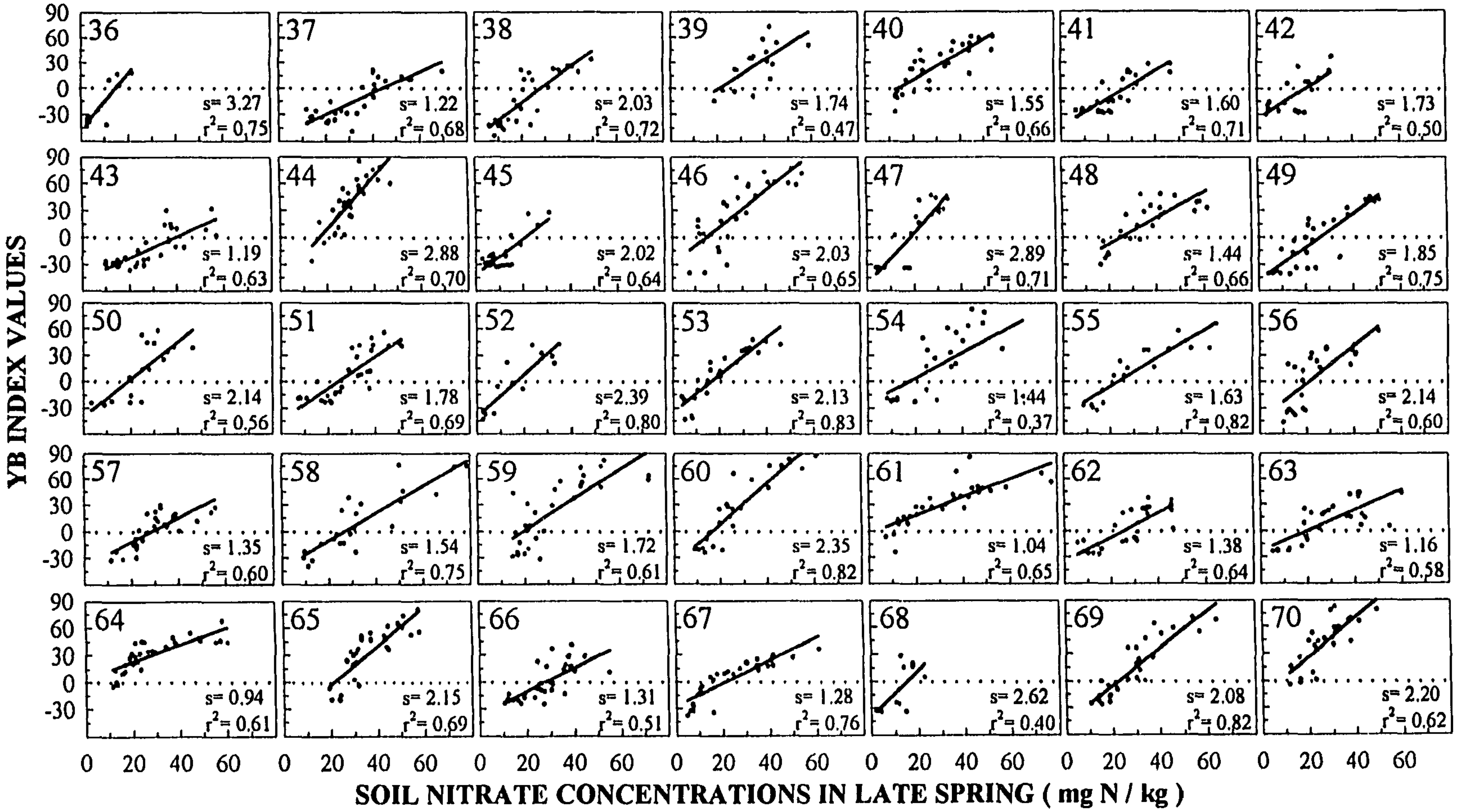



Figure 5. Within-trial relationships between YB index values and soil nitrate concentrations measured in late spring in 70 response trials where fertilizer N was applied in early spring.

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of 0.65, a standard deviation of 0.17. These observations suggest that the linear models using YB index values had essentially the same level of predictability as did the segmented models using cornstalk nitrate concentrations.

The $r^2$ values for models in Fig. 5 were slightly better than those for QRP models relating rate of N application to yields, which ranged from 0.0 to 0.96 and had a mean of 0.62 and a standard deviation of 0.28. YB index values also were linearly related to rates of N application, where $r^2$ values ranged from 0.43 to 0.94 and had a mean of 0.79 and a standard deviation of 0.10 (data not shown). These observations indicate that relationships based on YB index values described plant responses to fertilizer at least as well as commonly used relationships based on yields.

Relationships presented in Fig. 6 show that merely taking the logarithm of corn stalk nitrate concentrations was not adequate to linearize relationships with soil nitrate concentrations within individual sites. The YB index, therefore, offers clear advantages over a simple logarithm transformation.

*Utility of the Index:*

The Utility of the YB index is demonstrated if fig. 1 and 5 are compared for ability to identify the soil nitrate concentrations that resulted in optimal concentrations of nitrate in corn stalks and characterize variability in the soil nitrate concentration among sites. Relationships in Fig. 5 show that a YB index value of 0 usually corresponded to soil nitrate concentrations near 20-25 mg N/kg; across all 70 trials the mean and standard deviation of the soil nitrate concentrations corresponding to YB indexes of zero were 22.9 and 7.9 mg N/kg. Simple visual or statistical analysis can be used to assess the reliability of the determination in the range of practical interest, from an YB index of about -20 (100 mg N/kg ) to an YB index of 20.

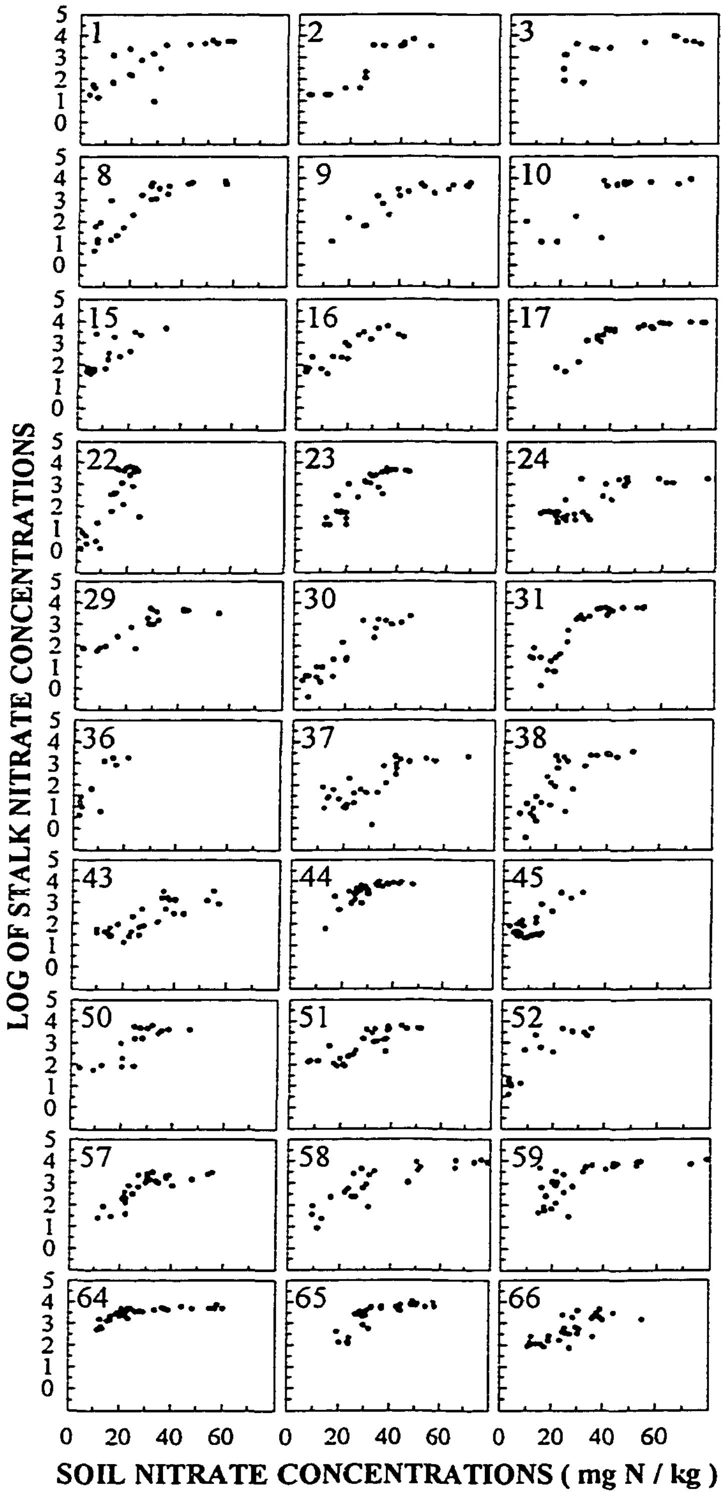


Figure 6. Within-trial relationships between logarithms of end-of-season stalk nitrate concentrations and concentrations of soil nitrate found in selected trials.

The same task is much more difficult if the relationships in Fig. 1 are analyzed because a much coarser scale must be used on the Y-axis. Moreover, the soil and stalk nitrate concentrations of interest fall close to the inflection point in the model and the exact point at which the inflection occurs often is difficult to establish. When data from many sites are pooled, the pooled data results in serious problems of the type noted in the discussion of Fig. 2.

Utility of the YB index becomes more evident if it is recognized that most studies include only three or four rates of N and that segmented models cannot be fit with so few rates. Under such conditions it would seem reasonable to use a linear model to relate stalk nitrate concentrations to soil nitrate concentrations. Indeed, comparisons of $r^2$ values seem to suggest that the linear models fit as well as the segmented models, even when many rates of N are used (Fig. 7).

Analyses of residuals (i.e., differences between predicted and observed values) reveal that the linear model imparts significant bias in the range of greatest interest (Fig. 8a). Although this problem can be detected when many rates of N are used, it would be difficult to detect when only a few rates of N are used. The analyses of residuals presented in Fig 8b and c show that the YB index method imparted even less bias than did the segmented model in the range of interest.

Excluding data from treatments that test extremely high or low (as done in the analyses presented in Fig. 8) should be considered a reasonable practice when using the YB index to describe relationships between soil and stalk nitrate concentrations in the near-optimal range. Indeed, the greatest advantage of using the YB index in response trials may be an increase in experimental efficiency by applying treatments only in the range expected to be near optimal. Treatments substantially above or below optimal are not needed because, unlike a single

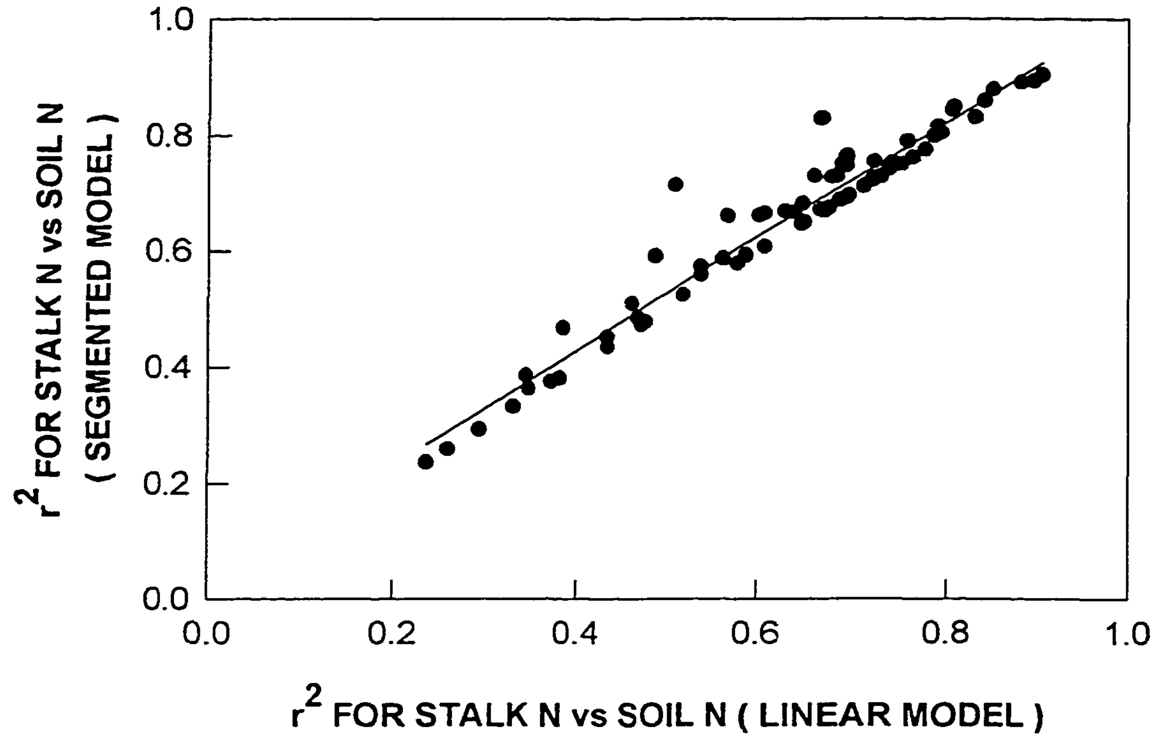


Fig. 7. Similarity of $r^2$ values for linear model and segmented model that relate end-of-season stalk nitrate concentrations to spring soil nitrate concentrations in individual trials.

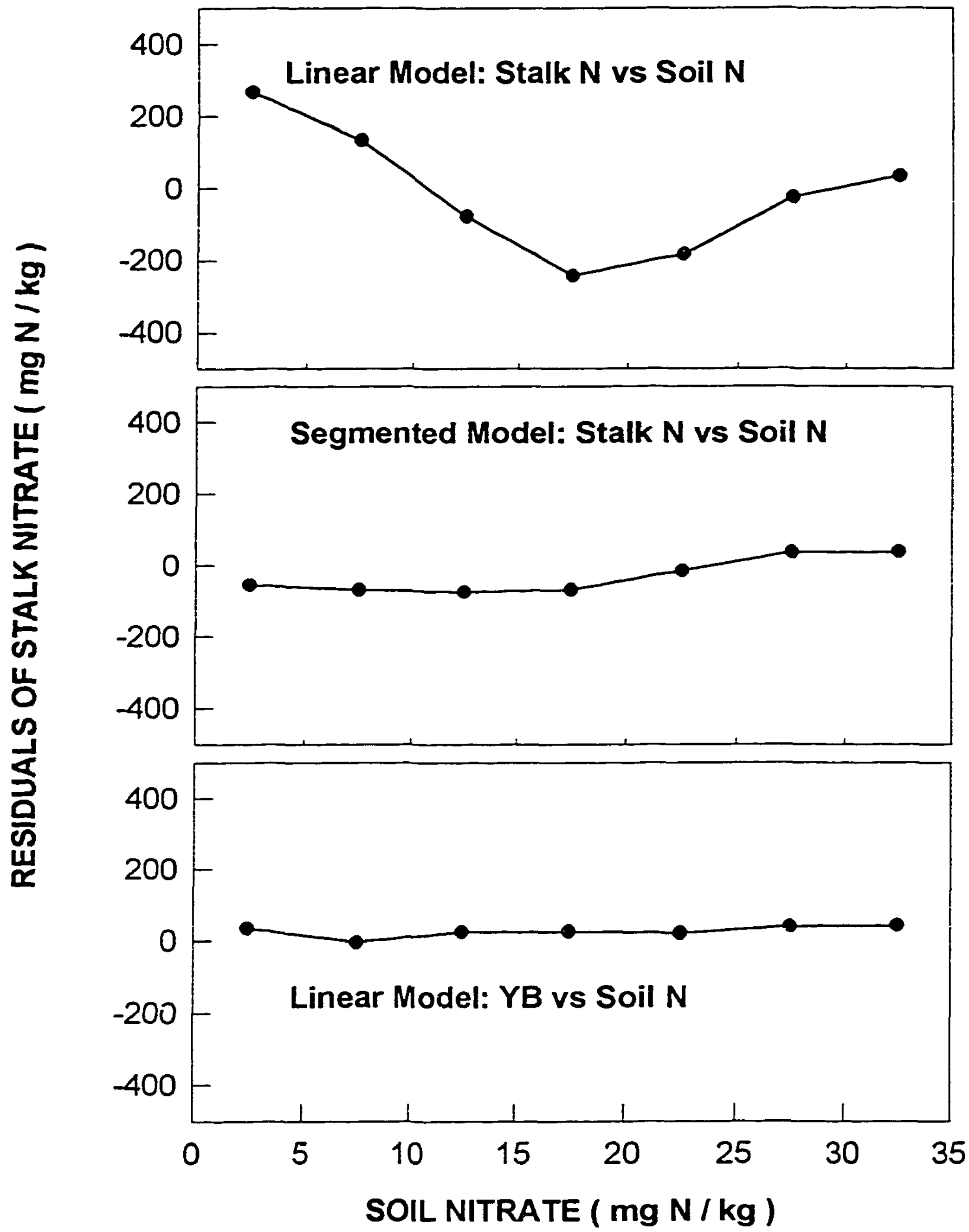


Fig. 8. Mean differences between observed and predicted stalk nitrate concentrations when various models are fit to each of 70 trials individually; (A) shows the differences when linear models are used to relate stalk nitrate concentrations to soil nitrate concentrations, (B) shows the differences when segmented models are used to relate stalk nitrate concentrations to soil nitrate concentrations, (C) shows the differences when linear models are used to relate YB index values to soil nitrate concentrations. YB indexes are transformed to stalk nitrate concentrations in part C to facilitate comparisons with parts A and B. Extreme stalk nitrate concentrations (<35 or >5000 mg N/kg) were excluded.

measurement of yields, a single measurement of stalk nitrate concentration provides an estimate of N supply relative to needs.

## Discussion

The YB index should be considered only a tool that aids in interpretation of end-of-season stalk nitrate concentrations, it does not describe some fundamental law or relationship. It is a measure of N sufficiency in corn plants because it is calculated from concentrations of nitrate measured on a single sample of cornstalks. It is a transformation of cornstalk nitrate concentrations that tends to form linear relationships with measured soil nitrate concentrations, and therefore, simplifies interpretation of results of the end-of-season stalk nitrate test.

The YB transformation is derived from an observed relationship between soil nitrate concentrations in late spring and stalk nitrate concentrations at the end of the season. The relationship has no fundamental meaning because, as discussed by Blackmer (1999), the soil nitrate concentrations cannot be considered perfect indicators of the N availability to plants if it is recognized that the concept of availability must consider proximity to roots at the time of plant need for N. As discussed by Blackmer (1999), problems related to defining N availability can be avoided by assuming that the soil test estimates sufficiency of N for corn growth and that the reliability of such estimates is established by degree of correlation with direct indicators of N sufficiency in plants.

Evidence that the soil test gave reasonable assessments of N sufficiency is provided by the finding that soil nitrate concentrations explained 57% of the variability in YB index values across the wide range of conditions included this study. This predictability should be considered relatively good because the corresponding pooled relationship between soil nitrate concentrations and yields showed no useful relationship (Fig 9a). Moreover, the pooled

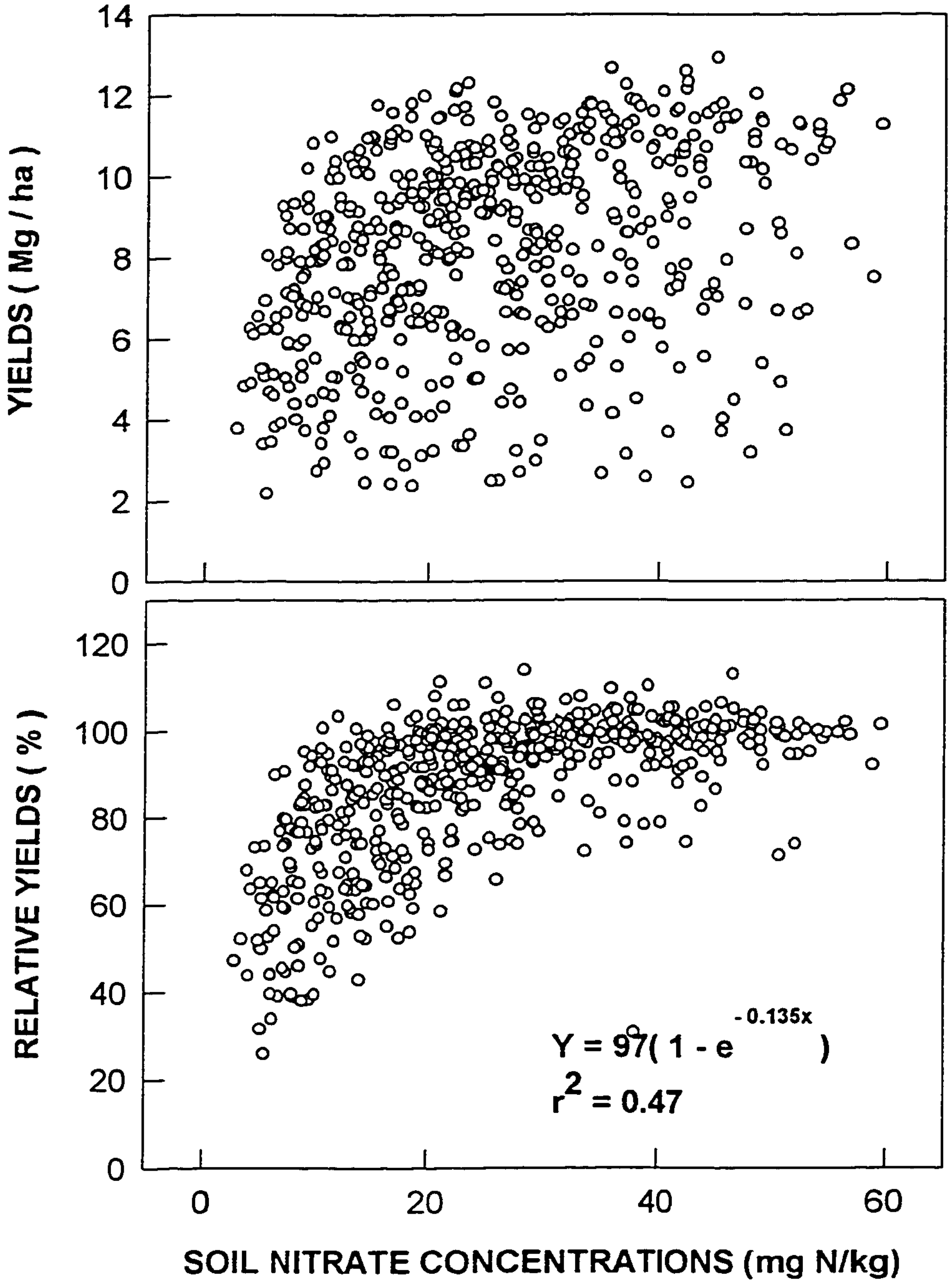


Fig. 9. Relationships between soil nitrate concentrations in late spring and (A) yield of corn grain or (B) relative yields of corn in 70 response trials in which at least 6 rates of N were applied in early spring.

relationship between soil nitrate concentrations and relatively yields (i.e., yields expressed as a percentage of the plateau on the QRP model for the trial) had a $r^2$ value of only 0.47 (Fig 9b).

Effective use of the YB index does not rest on the assumption that relationships between soil nitrate concentrations and YB index values are linear in any given situation. As indicated in Fig. 4, scattergrams quickly reveal whether or not linear relationships are observed within any given situation. The YB index does, however, provide a reference point for discussing differences among sites. Deviations from linearity and predictability of any model fit to relationships between soil test values and YB index values in individual trials provide a basis for characterizing differences in results among trials.

The slopes of the observed relationships between soil nitrate concentrations and YB index values also have meaning that helps to characterize differences among trials. The mean and standard deviation of slopes for the 70 relationships in this study was 1.93 and 0.76. Relatively high slopes clearly would be favored by efficient uptake of measured soil nitrate, by uptake of N not measured as nitrate but present in quantities proportional to measured nitrate concentrations, and by plants that need to take up relatively little N to satisfy their needs. Any reasonable analysis of the causes and meanings of differences in slope among the sites studied is beyond the scope of this paper, however, and should be deferred for discussions where the YB index is used to interpret data collected in specific trials conducted for specific purposes.

## Conclusions

The YB index is a new tool to aid in interpretation of results of the end-of-season test for cornstalk nitrate. It is calculated directly from stalk nitrate concentrations, but it provides a measure of N sufficiency that tends to be linearly related to concentrations of nitrate in soils in late spring. Although the tendency to form linear relationships avoids many problems, use of the index does not rely on the assumption that linear relationships are formed. The YB index should be especially useful in studies where too few rates are applied to use discontinuous models. Because effective studies can be conducted when only a few rates of N applied in the near-optimal range, use of the YB index offers the possibility of greatly increasing experimental efficiency in studies designed to fine-tune existing recommendations. The utility of the index needs to be more fully explored in discussions of studies examining the effects of site conditions on optimal rates, times, or methods of N application across many sites.

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# USE OF THE YB INDEX TO IDENTIFY OPTIMAL RATES OF NITROGEN FERTILIZATION FOR CORN

A paper to be submitted to the Agronomy Journal

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## Abstract

Better methods of identifying optimal rates of N fertilization for corn are needed for economic and environmental reasons. Studies were conducted to evaluate the potential of using relationships between rates of N application and YB index values to identify optimal rates. YB index values are calculated from end-of-season stalk nitrate concentrations, but they tend to linearly relate to concentrations of soil nitrate in late spring. Data were analyzed from 70 response trials where at least 6 rates of N were applied. Results showed that relationships between rates of N application and YB index values tended to be linear and have higher $r^2$ values than did commonly used models relating N rates to yields. Relationships using YB index values were clearly superior where grain yield responses were less than 1 Mg/ha. YB index values associated with maximum profit for producers were calculated, and rates of N application required to attain these values also were calculated. Comparisons of these profit maximizing rates using YB index with economic optimum rates calculated from yield response curves by traditional methods showed marked disagreements. The YB index offers great potential for improving N management in soils having relatively large amounts of plant-available N because traditional methods based on yield response do not work well under these conditions.

## Introduction

Economic optimum rates of N fertilization are determined by analysis of relationships between rates of N application and yields observed in field studies (Heady et al., 1955;

Heady and Dillon, 1961; Nelson et al., 1985; Black 1993; Colwell, 1994). Some type of curve is fit to describe the relationship, and the curve is used to identify the rate where the marginal costs of fertilization are equal to the marginal value of crop produced. Although the method requires many assumptions, economic optimum rates of fertilization are generally accepted as the rate of fertilization that would have maximized profit per area of land fertilized.

A limitation of this method is that yield increases tend to diminish with successive increments of applied fertilizer and economic optimum rates of fertilization for corn tend to occur where slopes are relatively flat. Relatively small errors in estimating the slope, therefore, can result in relatively large errors in optimal rates. The seriousness of this problem when selecting optimal rates of N for corn was demonstrated by Cerrato and Blackmer (1990) who showed that commonly used models tend to disagree substantially when identifying economic optimum rates of N fertilization. The comparisons were made using data from trials where 10 rates of N were applied, and analyses showed and that the disagreements among models could be attributed to subtle bias imposed as models are fit to the yield data.

The end-of-season test for cornstalk nitrate offers an alternative approach to identifying rates of N fertilization that were optimal in field experiments. This test was developed by Binford et al. (1990, 1992) and analyses presented showed that the test could be used to estimate optimal rates of N fertilization. This test measures the sufficiency (i.e., supply relative to need) of N for plant growth and can be used to assess the extent to which supplies of N fall above or below optimal. Result of cornstalk test are often difficult to analyze, however, due to the extremely wide range in nitrate concentrations encountered in response trials and nonlinear relationships between rates of N application and stalk nitrate concentrations.

Yang and Blackmer (1999) recently developed the YB index, which is a new tool that aids in interpretation of results from the end-of-season test for cornstalk nitrate. The YB index is a transformation developed to linearize observed relationships between concentrations of soil nitrate measured in late spring and concentrations of nitrate in cornstalks at the end of the season in trials where fertilizer N had been applied before planting. Results showed that relationships between the soil nitrate concentrations and YB index values within the trials offered great potential for characterizing differences among response trials. The utility of relationships between rates of N fertilization and YB index values was not explored.

Here we characterize relationships between rates of N fertilization and YB index values and explore the potential of using these relationships to identify optimal rates of fertilization. Better methods of measuring optimal rates of fertilization could help address economic and environmental concerns discussed in many recent reviews. We reason that ability to identify optimal rates of fertilization is an essential first step in any effort to weigh the costs and benefits of alternative management practices.

## Materials and Methods

Data were taken from a total of 1813 plots from 70 N-response trials conducted in Iowa over a period of six years (1986 - 1991). For the purpose of this paper, a trial means application N at several rates at one site at one time by using only one method of application. Most of the response trials are described by Davis (1992), Binford et al. (1992), and Meese (1993). Each trial involved application of at least six rates of N to replicated and randomized plots before corn was planted. Fertilizer N was applied in the form of urea, ammonium nitrate or anhydrous ammonia in either late fall of the previous year or the early spring. Preceding crops were corn or soybean. Measurements taken from each trial included concentrations of nitrate in the surface 30-cm layer of soil when corn plants were 15 to 30 cm tall and concentrations of nitrate in the cornstalks in the lower portion of cornstalks one to three weeks after black layers had formed on most kernels. Soil samples were composites of at least 8 cores and stalk samples of 15 twenty-cm stalk segments (15 to 35 cm above the ground). Nitrate concentrations in the soil and stalk samples were determined by either automated colorimetric procedures or by ion selective electrodes and expressed on the basis of dry soil or stalks.

Mean net returns to fertilization that would have been obtained across 70 response trials if fertilizer N had been applied only in quantities needed to attain various YB index values were calculated as follows: First, a straight line was fit to describe the N rate–YB index relationship in each trial. N rates corresponding to a series of selected YB index values (from -40 to 40 at every 5 unit interval) are then determined from the linear equation in each trial. Net returns for those N rates were then calculated by subtracting the fertilizer costs in terms of amounts of grain from the yield increments of fertilization as predicted by the QRP yield model at different price ratios of grain ($/ton) to N ($/kg) in each trial. Finally, the net returns at each of the selected YB index value were averaged across all 70 trials.

Profit–maximizing YB index values at different ratios of prices for grain and fertilizer N were identified by first constructing curves of the mean net returns to fertilization with respect to YB index values. The YB index value corresponding to the highest mean net returns is the profit–maximizing YB index value.

Mean net returns to fertilization that would have been obtained if fertilizer N had been applied at selected rates that deviate from the economic optimum were calculated as follows: First, regression analysis was performed to obtain the yield curve using a commonly used model in each trial, and the economic optimal rates at different price ratios were determined using the equation obtained from regression. Net returns were then calculated by subtracting the fertilizer costs in terms of amounts of grain from the yield increments of fertilization as predicted by the selected yield model at different price ratios of grain ($/ton) to N ($/kg) for N rates ranging from 200 kg N/ha below to 200 kg N/ha above the economic optimal at 20 kg N/ha interval in each trial. The net returns at those selected N rates relative to the economic optimum were then averaged across all 70 trials for each combination of price ratio and yield model.

Terminology is carefully selected in this report to recognize the important difference between *ex post* and *ex ante* optimal rates of fertilization. This report addresses only *ex post* optimal rates, which are after-the-fact assessments of optimal rates for the specific conditions studied. These assessments should not be confused with *ex ante* optimal rates, which are estimates of rates that are most likely to be optimal under conditions where unknown weather and other factors introduce uncertainty (Babcock and Blackmer, 1994; Bullock and Bullock, 1994). Estimates of *ex post* optimal rates are important because estimates of *ex ante* optimal rates are calculated from estimates of *ex post* optimal rates.

In accordance with common practice, the term "economic optimum rate(s) of fertilization" is used to denote rates that were identified as being optimal by specific and commonly used methods. It should be recognized, however, that these are estimates of *ex post* optimal rates rather than true *ex post* optimal rates. We have used the phrase "economically optimal rate(s)" to denote the rate we are trying to identify and the phrase "economic optimum rate(s)" to denote estimate obtained by using commonly used methods. The underlying problem addressed is that the phrase "economic optimum rate(s) of fertilization has been widely used to describe rates that are not really optimal economically.

Analysis of variance and segmented model regression analysis (Waugh et al., 1973) were performed using ANOVA and NLIN procedures of the SAS systems for windows, version 6.12 (SAS Institute, 1989). Quadratic model, quadratic response plateau model, and the Mitscherlich model regressions were also done using the NLIN procedure of the same SAS package.

## Results

*Rate-Yield Relationships:*

Yields observed at various rates of N fertilization in each of the 70 trials are presented in Fig. 1. The trials are listed in order of decreasing $r^2$ values of QRP models fit to the data to be consistent with another paper (Yang and blackmer, 1999). Models are not presented in Fig. 1, however, due to uncertainty concerning which model should be used.

Table 1 shows $r^2$ values for four commonly used models, and they tended to be similar among the models for any given site. Fit of the models was not statistically significant ($p = 0.05$) at 19 to 23 of the 70 trials.

Data presented in Table 1 show that the models often showed considerable disagreement when used to identify economic optimum rates of N fertilization at a single grain-to-fertilizer price ratio. Mean economic optimum rates for models ranged from 124 to 199 kg N/ha, and disagreements among models within sites often were much greater. Lack of statistically significant relationships suggested that 0 kg N/ha was the economic optimum rate of fertilization at many sites. Models that have relatively poor $r^2$ values and indicate

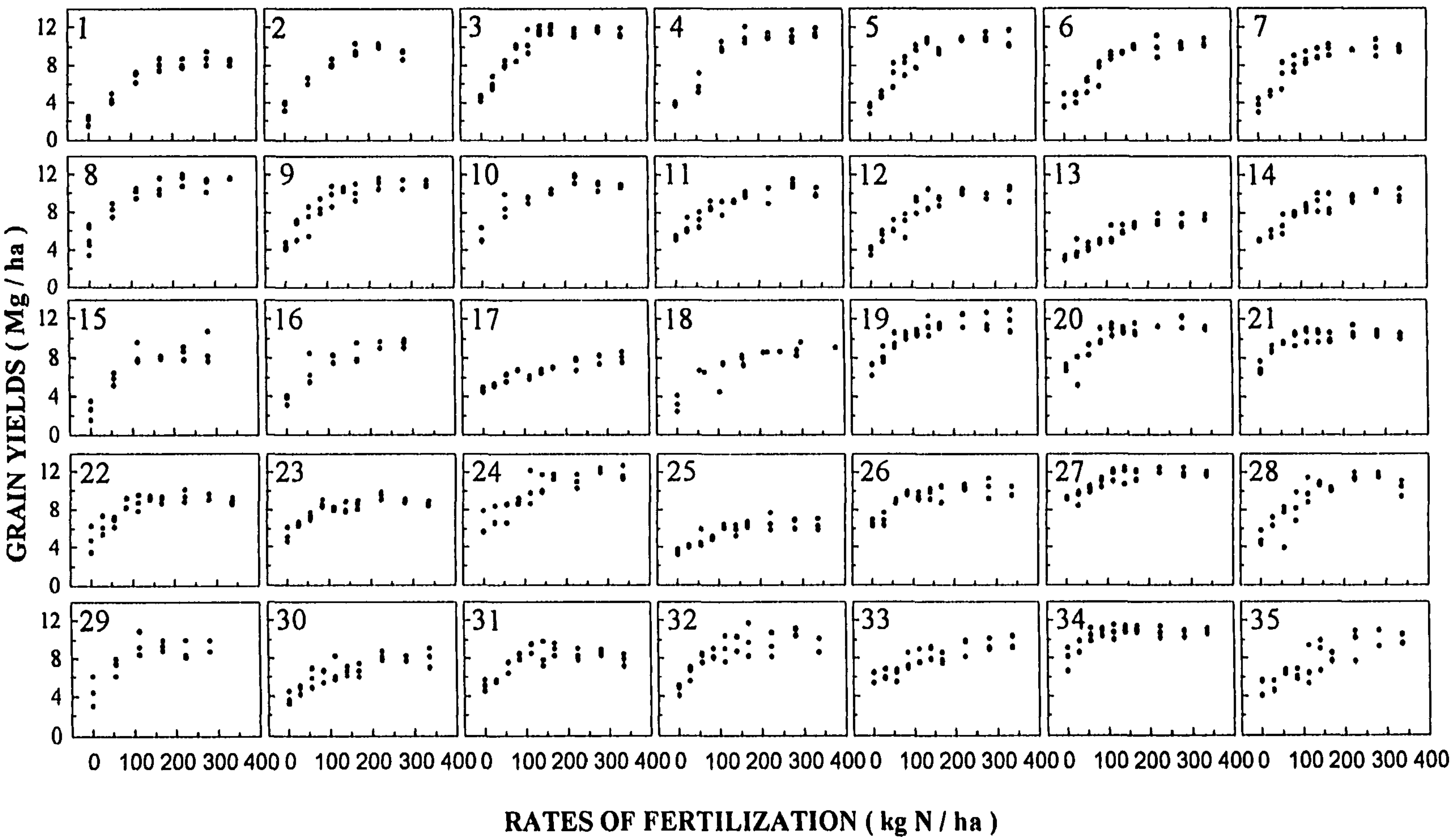



Figure 1. Yields observed in 70 response trials where fertilizer N was applied at various rates before crops were planted.

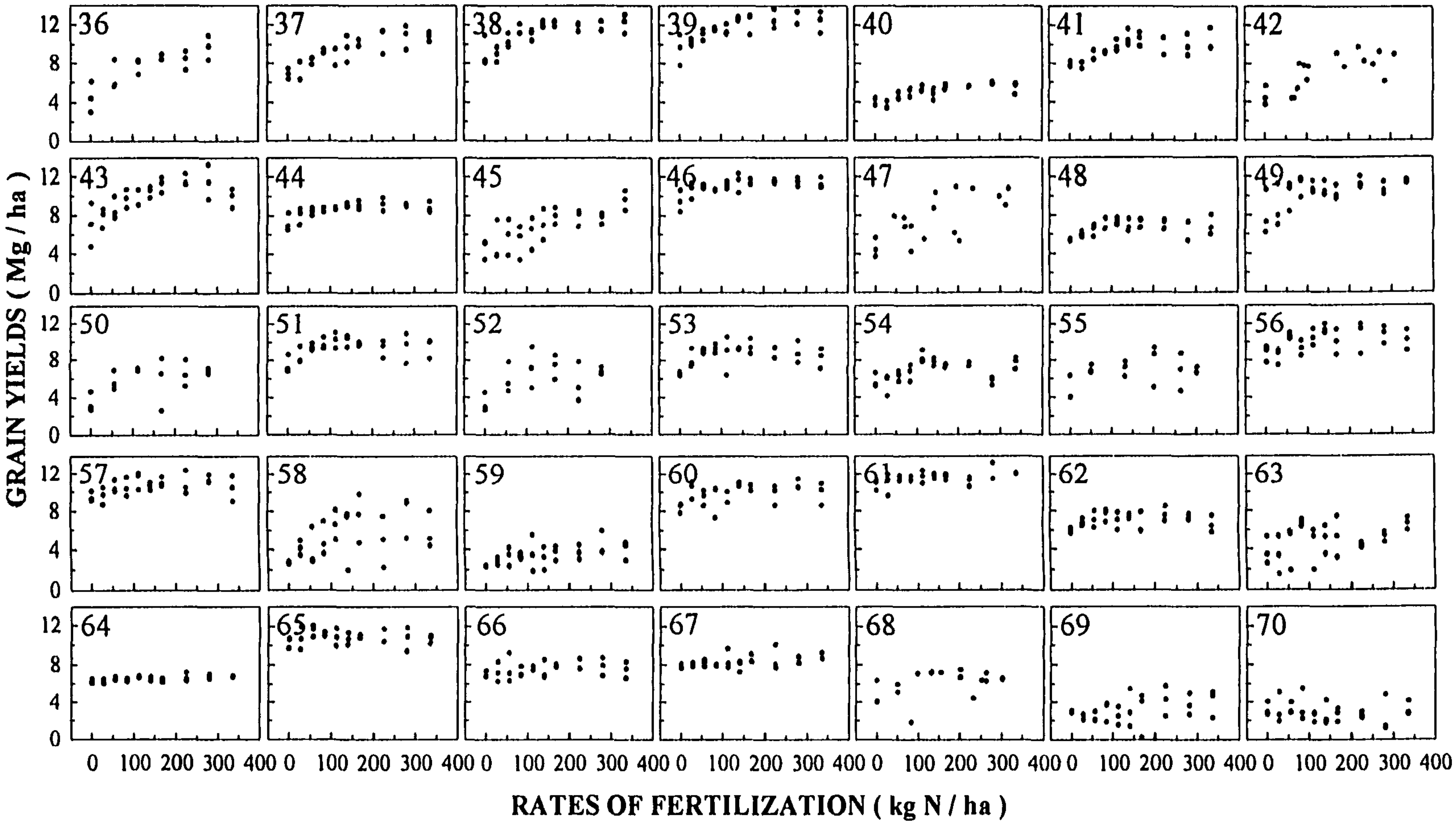



Figure 1. Continued.

Table 1. Coefficients of determination ($r^2$ values) for various models fit to data from the 70 response trials shown in Figure 1 and economic optimum rates of fertilization calculated from these models by assuming that 1 Mg of grain and 200 kg of N have equal values.

| Trials | $r^2$ values | | | | optimum rates | | | |
|---|---|---|---|---|---|---|---|---|
| | LRP | QRP | MITS | QUAD | LRP | QRP | MITS | QUAD |
| 1 | 0.97 | 0.96 | 0.96 | 0.96 | 149 | 216 | 268 | 239 |
| 2 | 0.96 | 0.96 | 0.94 | 0.97 | 143 | 191 | 231 | 197 |
| 3 | 0.95 | 0.95 | 0.93 | 0.93 | 127 | 169 | 218 | 216 |
| 4 | 0.96 | 0.94 | 0.92 | 0.93 | 139 | 202 | 274 | 238 |
| 5 | 0.92 | 0.92 | 0.92 | 0.91 | 133 | 193 | 248 | 230 |
| 6 | 0.93 | 0.92 | 0.90 | 0.91 | 152 | 208 | 276 | 237 |
| 7 | 0.90 | 0.91 | 0.91 | 0.89 | 123 | 172 | 212 | 220 |
| 8 | 0.91 | 0.91 | 0.91 | 0.90 | 129 | 182 | 213 | 227 |
| 9 | 0.89 | 0.90 | 0.90 | 0.89 | 132 | 201 | 249 | 235 |
| 10 | 0.86 | 0.89 | 0.90 | 0.89 | 143 | 204 | 209 | 223 |
| 11 | 0.87 | 0.89 | 0.89 | 0.90 | 166 | 226 | 249 | 233 |
| 12 | 0.88 | 0.89 | 0.88 | 0.88 | 152 | 214 | 259 | 235 |
| 13 | 0.89 | 0.89 | 0.88 | 0.89 | 199 | 255 | 298 | 258 |
| 14 | 0.86 | 0.88 | 0.88 | 0.88 | 150 | 230 | 257 | 239 |
| 15 | 0.87 | 0.87 | 0.87 | 0.84 | 101 | 144 | 192 | 197 |
| 16 | 0.84 | 0.87 | 0.88 | 0.87 | 133 | 205 | 228 | 218 |
| 17 | 0.84 | 0.86 | 0.86 | 0.86 | 254 | 267 | 274 | 270 |
| 18 | 0.84 | 0.85 | 0.86 | 0.85 | 185 | 238 | 267 | 263 |
| 19 | 0.82 | 0.85 | 0.86 | 0.84 | 144 | 182 | 198 | 217 |
| 20 | 0.84 | 0.84 | 0.83 | 0.83 | 111 | 167 | 200 | 211 |
| 21 | 0.82 | 0.83 | 0.84 | 0.73 | 68 | 96 | 108 | 182 |
| 22 | 0.84 | 0.83 | 0.82 | 0.82 | 97 | 144 | 168 | 199 |
| 23 | 0.84 | 0.83 | 0.85 | 0.83 | 87 | 140 | 156 | 197 |
| 24 | 0.83 | 0.82 | 0.82 | 0.82 | 170 | 242 | 296 | 250 |
| 25 | 0.80 | 0.81 | 0.80 | 0.82 | 154 | 183 | 181 | 201 |
| 26 | 0.82 | 0.81 | 0.81 | 0.79 | 89 | 140 | 164 | 202 |
| 27 | 0.82 | 0.81 | 0.78 | 0.81 | 125 | 171 | 175 | 194 |
| 28 | 0.81 | 0.80 | 0.78 | 0.82 | 144 | 211 | 254 | 222 |
| 29 | 0.80 | 0.79 | 0.77 | 0.74 | 101 | 134 | 161 | 183 |
| 30 | 0.75 | 0.77 | 0.78 | 0.77 | 213 | 234 | 239 | 242 |
| 31 | 0.79 | 0.77 | 0.72 | 0.75 | 92 | 118 | 135 | 179 |
| 32 | 0.73 | 0.75 | 0.75 | 0.75 | 121 | 149 | 170 | 203 |
| 33 | 0.75 | 0.75 | 0.75 | 0.75 | 223 | 275 | 322 | 272 |
| 34 | 0.76 | 0.75 | 0.73 | 0.63 | 66 | 92 | 105 | 172 |
| 35 | 0.75 | 0.74 | 0.70 | 0.74 | 234 | 315 | 322 | 314 |

Table 1. Continue

| Trials | r2 values | | | | optimum rates | | | |
|---|---|---|---|---|---|---|---|---|
| | LRP | QRP | MITS | QUAD | LRP | QRP | MITS | QUAD |
| 36 | 0.71 | 0.72 | 0.73 | 0.72 | 146 | 239 | 256 | 238 |
| 37 | 0.72 | 0.72 | 0.71 | 0.72 | 201 | 253 | 281 | 252 |
| 38 | 0.70 | 0.70 | 0.67 | 0.67 | 137 | 162 | 173 | 199 |
| 39 | 0.66 | 0.67 | 0.66 | 0.67 | 140 | 176 | 173 | 199 |
| 40 | 0.64 | 0.65 | 0.64 | 0.66 | 185 | 172 | 148 | 172 |
| 41 | 0.67 | 0.64 | 0.60 | 0.61 | 140 | 156 | 158 | 186 |
| 42 | 0.65 | 0.63 | 0.61 | 0.63 | 164 | 214 | 277 | 214 |
| 43 | 0.61 | 0.61 | 0.59 | 0.66 | 159 | 189 | 191 | 196 |
| 44 | 0.59 | 0.61 | 0.61 | 0.61 | 96 | 120 | 103 | 154 |
| 45 | 0.53 | 0.56 | 0.50 | 0.56 | 214 | 573 | 312 | 578 |
| 46 | 0.48 | 0.49 | 0.52 | 0.49 | 43 | 72 | 96 | 153 |
| 47 | 0.48 | 0.48 | 0.45 | 0.48 | 269 | 389 | 268 | 392 |
| 48 | 0.47 | 0.47 | 0.44 | 0.42 | 86 | 97 | 86 | 141 |
| 49 | 0.47 | 0.46 | 0.45 | 0.39 | 82 | 107 | 132 | 195 |
| 50 | 0.45 | 0.45 | 0.44 | 0.37 | 75 | 102 | 100 | 169 |
| 51 | 0.45 | 0.45 | 0.43 | 0.38 | 66 | 87 | 85 | 150 |
| 52 | 0.42 | 0.42 | 0.41 | 0.36 | 71 | 96 | 91 | 154 |
| 53 | 0.41 | 0.41 | 0.40 | 0.35 | 43 | 60 | 65 | 145 |
| 54 | 0.41 | 0.37 | 0.32 | 0.32 | 112 | 120 | 109 | 154 |
| 55 | 0.35 | 0.35 | 0.35 | 0.30 | 47 | 62 | 59 | 151 |
| 56 | 0.32 | 0.31 | 0.30 | 0.31 | 127 | 128 | 121 | 165 |
| 57 | 0.30 | 0.31 | 0.29 | 0.32 | 80 | 105 | 97 | 145 |
| 58 | 0.31 | 0.30 | 0.30 | 0.30 | 115 | 159 | 171 | 198 |
| 59 | 0.22 | 0.27 | 0.27 | 0.27 | 121 | 146 | 130 | 147 |
| 60 | 0.25 | 0.25 | 0.25 | 0.22 | 22 | 26 | 17 | 143 |
| 61 | 0.23 | 0.24 | 0.25 | 0.23 | 70 | 93 | 78 | 36 |
| 62 | 0.21 | 0.21 | 0.21 | 0.20 | 39 | 54 | 48 | 105 |
| 63 | 0.18 | 0.15 | 0.15 | 0.14 | 84 | 93 | 130 | 243 |
| 64 | 0.18 | 0.09 | 0.11 | 0.26 | 63 | 5 | 0 | 0 |
| 65 | 0.09 | 0.08 | 0.08 | 0.06 | 48 | 46 | 31 | 12 |
| 66 | 0.05 | 0.08 | 0.07 | 0.09 | 70 | 0 | 32 | 43 |
| 67 | 0.23 | 0.08 | 0.14 | 0.23 | 0 | 11 | 63 | 0 |
| 68 | 0.27 | 0.06 | 0.22 | 0.23 | 133 | 22 | 146 | 160 |
| 69 | 0.16 | 0.00 | 0.00 | 0.16 | 266 | 7 | 422 | 176 |
| 70 | 0.01 | 0.00 | 0.00 | 0.06 | 0 | 0 | 0 | 332 |
| Mean | 0.62 | 0.62 | 0.61 | 0.61 | 124 | 158 | 177 | 199 |
| Stdev | 0.27 | 0.29 | 0.28 | 0.27 | 59 | 94 | 90 | 82 |

relatively high economic optimum rates are a special problem because arbitrary decisions concerning how such sites are handled can have great influence on final interpretations of all data collected.

Data presented in Table 2 show that the models agreed that economic optimum rates of N fertilization tended to increase with grain-to-fertilizer price ratio. However, the models disagreed greatly concerning the magnitude of the effect. The LRP model indicated that rates of fertilization should be increased by a mean of 15 kg N/ha as price ratios increased from 100 to 400 if only sites with statistically significant models were fit. The MITS model indicated that rates of fertilization should be increased by 126 kg N/ha under the same conditions. Different mean effects are calculated if it is assumed that 0 kg/ha is the economic optimum rate of N fertilization where fit of the models is not statistically significant.

As pointed out by Cerrato and Blackmer (1990) models tend to disagree when identifying economic optimum rates of fertilization because each model imparts a slightly different bias when fit to data. Disagreements concerning the effects of price ratios on economic optimum rates are caused by differences in the location and the nature of this bias. This problem is difficult to solve because economic optimum rates of fertilization are calculated from slopes of response curves and because yield response curves tend to have relatively small slopes at economic optimum rates of fertilization. Even a subtle bias in slope, therefore, can result in an important difference in economic optimum rate identified.

*Rate-Index Relationships:*

Results from the 70 trials show that relationships between rates of N application and YB index values tend to be linear (Fig. 2). This tendency is not surprising because the YB index was developed to linearize relationships between concentrations of soil nitrate in late spring and

Table 2. Means of economic optimum rates of N fertilization at various fertilizer-to-grain price ratios as indicated by various models.

| Site | Model | Optimum rates at various price ratios | | |
|---|---|---|---|---|
| | | 100 | 200 | 400 |
| | | ------------------ Kg N/ha ------------------ | | |
| Responsive* | LRP | 138 | 142 | 142 |
| | QRP | 159 | 195 | 212 |
| | MITS | 147 | 211 | 275 |
| | QUAD | 179 | 225 | 248 |
| ALL** | LRP | 114 | 124 | 128 |
| | QRP | 127 | 158 | 176 |
| | MITS | 116 | 177 | 243 |
| | QUAD | 159 | 199 | 229 |

* Only sites with maximum return of 1 Mg/ha or above were included.

** All 70 sites were included.

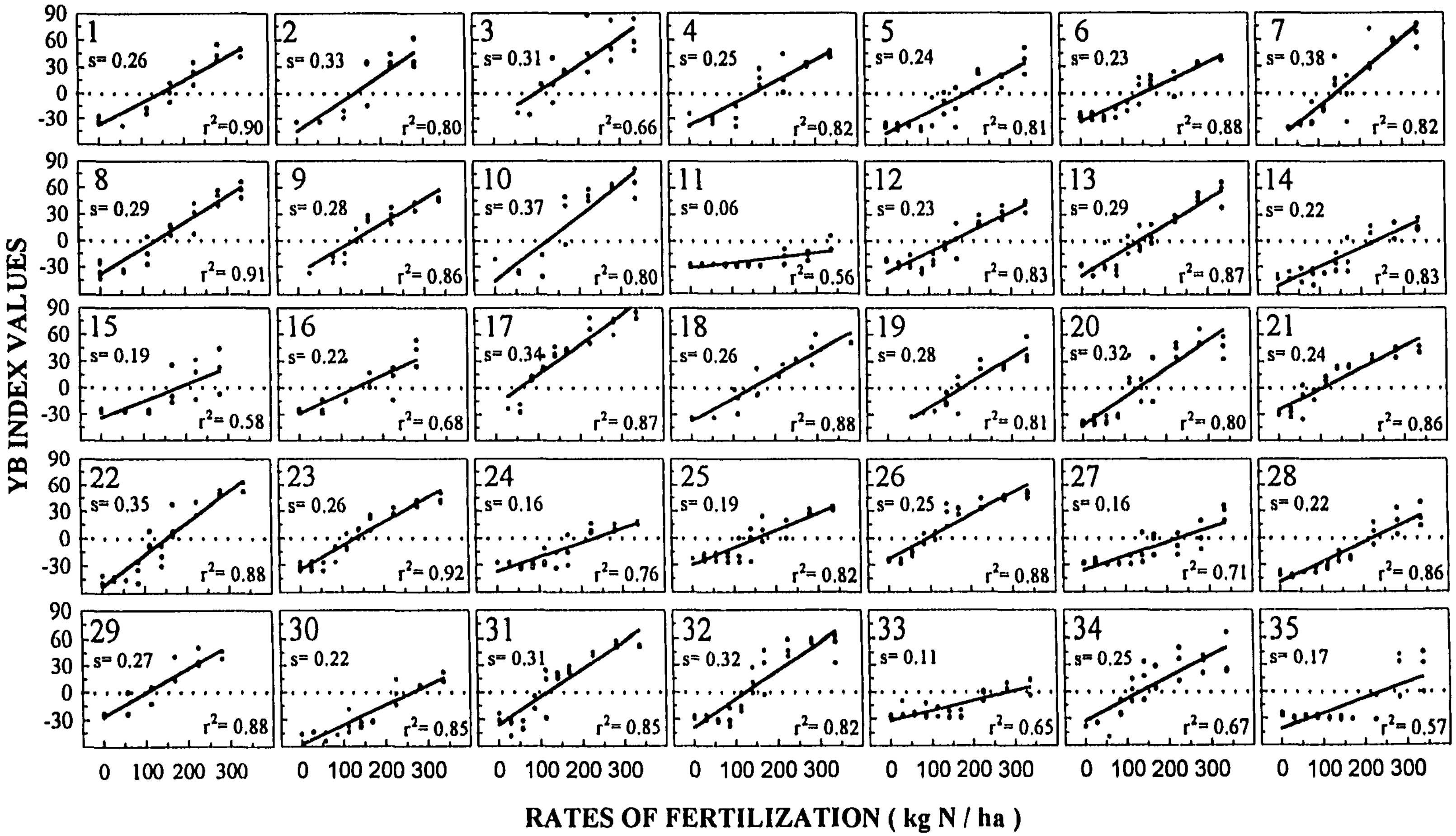



Figure 2. Relationships between rates of N fertilization and YB index values in 70 response trials where fertilizer N was applied at various rates before crops were planted.

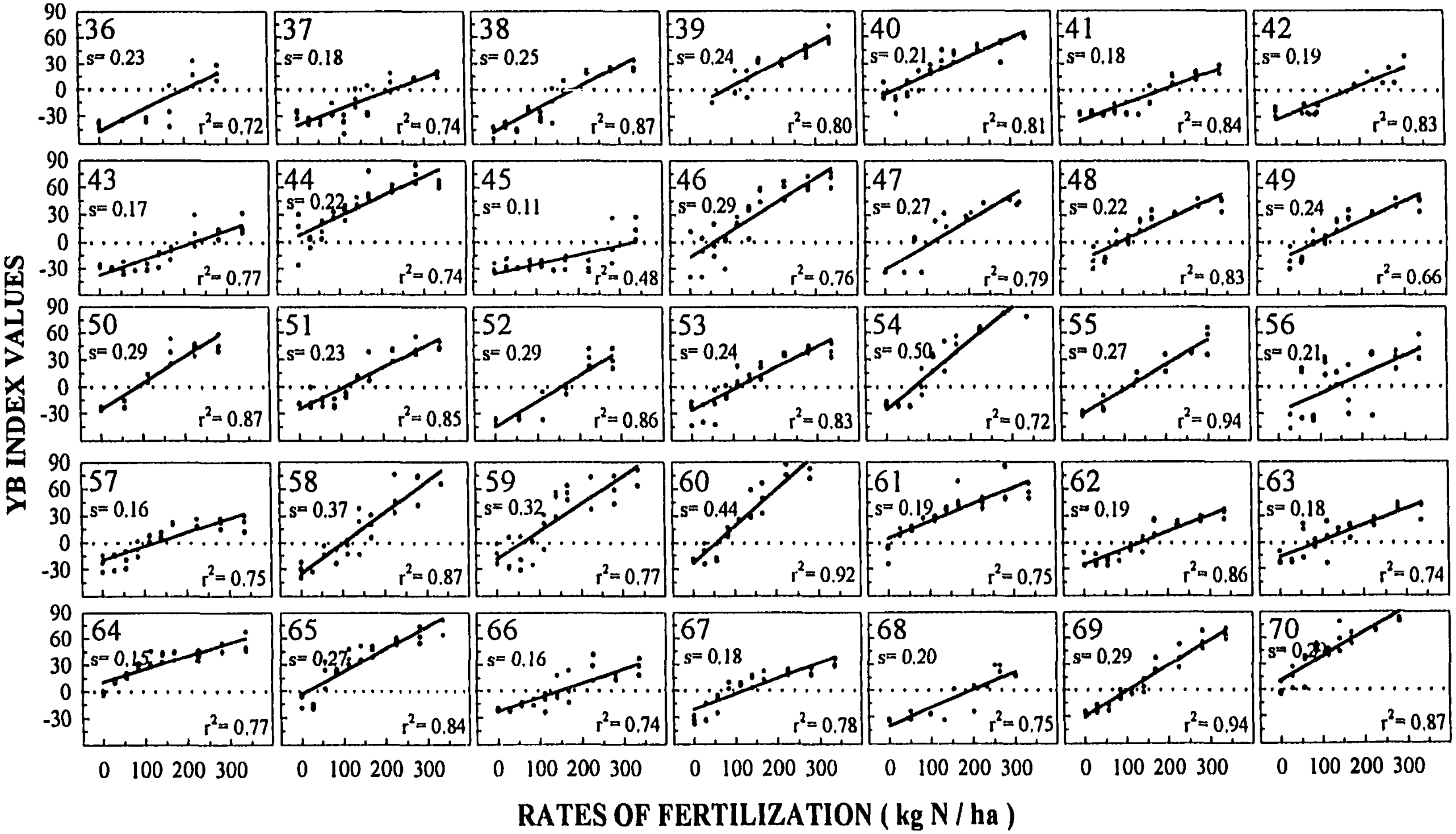



Figure 2. Continued.

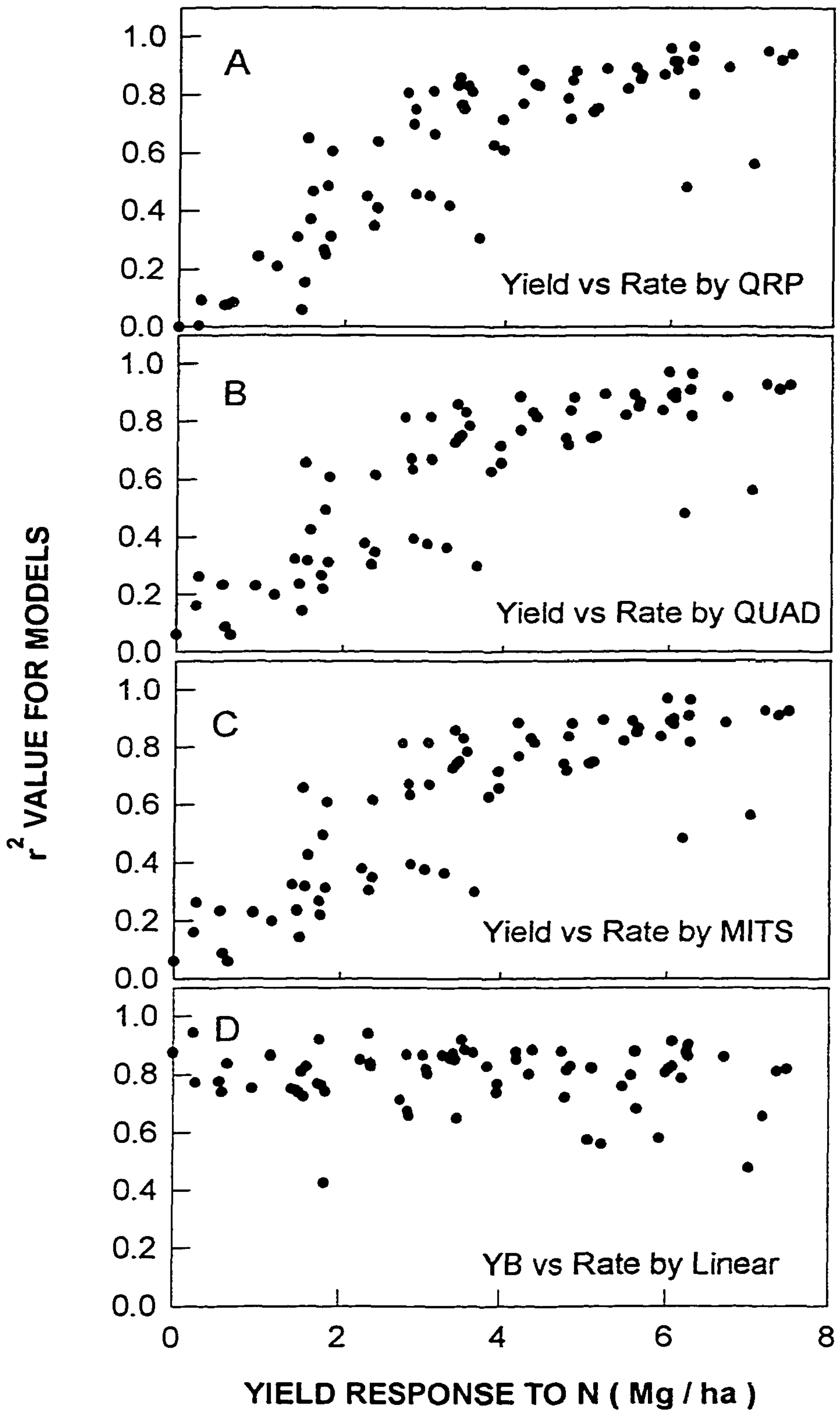
concentrations of cornstalk nitrate at the end of the season in trials where various rates of N were applied in early spring. A tendency for linear relationships between rates of N fertilization and soil nitrate concentrations should be expected under such conditions.

Linear models relating rates of N application to YB index values tended to have slightly better predictability than did the corresponding linear models relating soil nitrate concentrations to YB index values. For the rate-index relationships, $r^2$ values had a mean of 0.78, a standard deviation of 0.11, and a range of 0.42 to 0.94. For the soil nitrate-index relationships, $r^2$ values had a mean of 0.66, a standard deviation of 0.13, and a range of 0.32 to 0.87. The most likely explanation for this difference is that the precision of fertilizer applications was better than the precision of determinations of nitrate concentrations in the plots. Such determinations can include substantial errors due to sampling or analysis, and substantial errors in a small percentage of the samples could account for the difference.

An important finding is that observed relationships between rates of N fertilization and YB index values tended to have substantially better predictability than did relationships between rates of fertilization and yields as described by any of the models listed in Table 1. An important difference is that the yield response models had many low $r^2$ values whereas relationships with the YB index had no $r^2$ values less than 0.42, which is statistically significant at the 0.05 level of confidence.

Analyses presented in Fig. 3 reveal a basic difference between rate-index relationships and rate-yield relationships. The difference is that rate-index relationships had much higher $r^2$ values than did any of the rate-yield relationships on sites that showed relatively little response to N. This difference occurs because, unlike measured yields, the YB index shows responses to fertilizer within and above the range of rates identified as economic optimum by the various

Fig. 3. Relationships between observed yield response to fertilizer N and $r^2$ values for alternative models of crop response to N. The models in A, B and C are based on yield response and the model in D is based on response of the YB index.


A
Yield vs Rate by QRP
B
Yield vs Rate by QUAD
C
Yield vs Rate by MITS
D
YB vs Rate by Linear
r² VALUE FOR MODELS
YIELD RESPONSE TO N ( Mg / ha )
0.0
0.2
0.4
0.6
0.8
1.0
0
2
4
6
8

yield response models. Relationships based on YB index, therefore, offer a clear advantage over the relationships based on yields in situations where yield responses are small.

*Profit-Maximizing YB Index values:*

Established methods for calculating economic optimum rates of fertilization cannot be used with linear relationships between rates of N application and YB index values. The established methods are not needed because, unlike a single yield measurement, each YB index value provides an independent assessment of N sufficiency (i.e., supply relative to needs) for crop growth. Moreover, the YB index values provide a basis for describing N-sufficiency level on a numerical scale that extends from extreme deficiencies to extreme excesses of N. A necessary task, therefore, is to identify the economically optimal YB index value for any given situation.

YB index values that would have maximized profits for producers can be calculated if is assumed that each of the 70 sites should be fertilized to attain the same level of N sufficiency and that this sufficiency level should result in the greatest profit for a producer who managed all these sites. Under such conditions, the desired YB index value is the one corresponding to the highest net returns within a price ratio. Fitting QUAD model to the six highest returns within each price ratio and solving for the maximum returns indicated that 4, 14 and 24 were the profit maximizing YB index values for price ratios of 100, 200 and 400.

Figure 4 shows mean net returns to fertilization that would have been obtained if fertilizers were added in the exact amounts needed to attain various YB index values. Different relationships are presented for various grain-to-fertilizer price ratios. Mean net returns are expressed in terms of grain yields to avoid the need to assume actual prices, but net returns to fertilization can be easily expressed as $/ha by assuming a grain price.

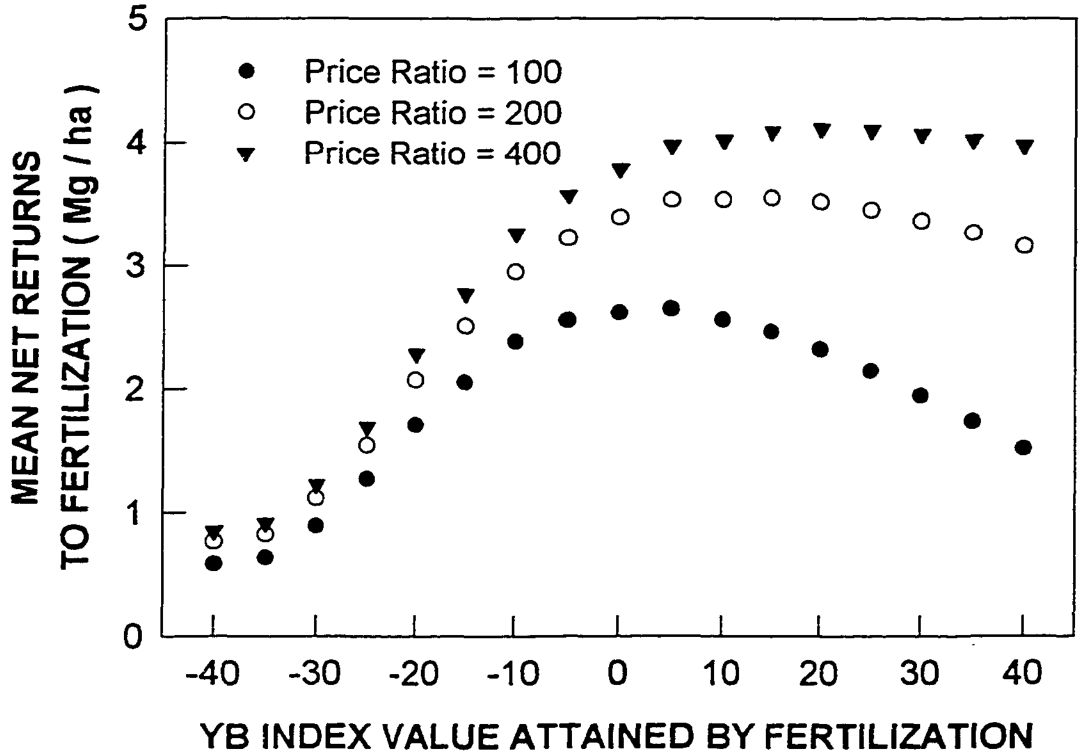



Fig. 4. Mean net returns to fertilization across 70 sites where N was applied to each site at the rate required to attain various YB index values within various price scenarios.

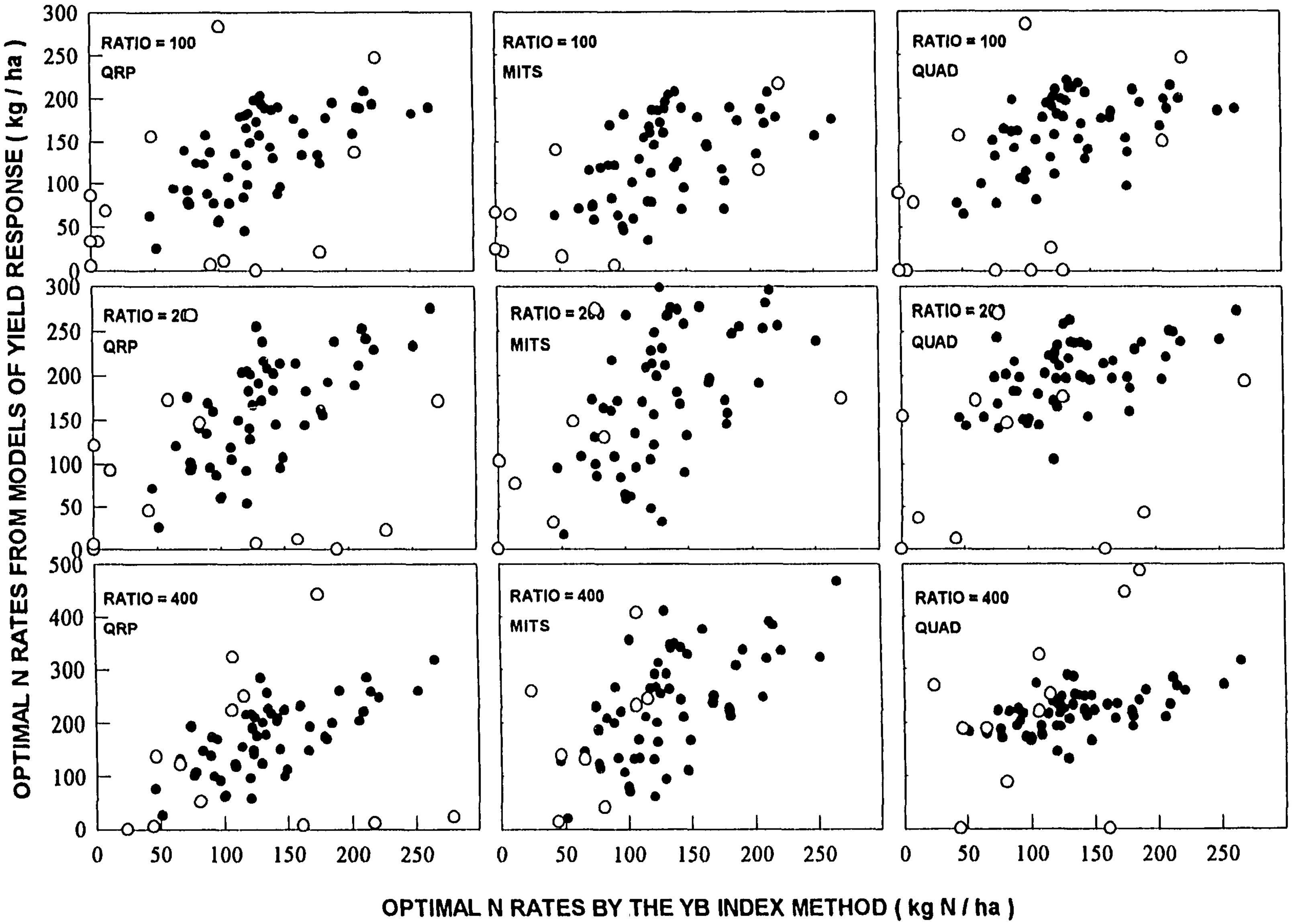
Across all sites, the mean rates of N fertilization required to attain the profit-maximizing YB index values were 135, 175 and 217 kg N/ha at grain-to-fertilizer price ratios are such that 1 Mg of grain buys 100, 200 or 400 kg of N. These rates fall within the ranges of rates identified by other commonly used models (Table 2), but this comparison does not provide much useful information because the other models disagree greatly among themselves. These optimal rates are higher than those identified by the QRP model when all sites are considered. This comparison is not good, however, because fit of the QRP model was not statistically significant at many sites and it was necessary to assume that the optimal rate was assumed to be 0 kg N/ha at these sites.

When only sites where all the yield response models were statistically significant were considered, the YB index method indicated optimal rates (151, 193, and 234 kg N/ha at price ratios of 100 200, 1nd 400) that were similar to those indicated by the QRP model. Cerrato and Blackmer (1990) indicated that this model probably is the best of the models considered. Unlike the YB index methods, however, use of the quadratic model leaves important questions about how to treat data from sites that show no significant response to fertilizer.

*Disagreements Among Models:*

Relatively poor agreement was observed between optimal rates of fertilization as indicated by the YB index method and by conventional methods based on models of yield response (Fig. 5). Depending on price ratio and yield response model used, $r^2$ values ranged from 0.07 to 0.49 (Table 3). This indicates a problem because good agreement should be expected if both methods were reliable.

Figure 5. Relationships between optimal rates of fertilization as indicated by YB index method and economic optimum rates of N fertilization as indicated by various models describing relationships between N rates and yields. Comparisons are made within each of the grain-to-fertilizer ratios. Solid points indicate optimal rates calculated only from models that were statistically significant, open circles indicate optimal rates calculated in situations where at least one of the models was not statistically significant.


RATIO = 100
QRP
RATIO = 100
MITS
RATIO = 100
QUAD
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QRP
RATIO = 200
MITS
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QUAD
RATIO = 400
QRP
RATIO = 400
MITS
RATIO = 400
QUAD
OPTIMAL N RATES FROM MODELS OF YIELD RESPONSE ( kg / ha )
OPTIMAL N RATES BY THE YB INDEX METHOD ( kg N / ha )

Table 3. Statistics describing linear relationships between economic optimum rates of fertilization and rates identified as optimal by the YB index method. Effect of grain-to-fertilizer price ratios and model used to calculate the economic optimal rates are shown.

| Trials | Price | r2 values | | | Intercept | | | Slope | | |
|---|---|---|---|---|---|---|---|---|---|---|
| included | ratio | QRP | MITS | QUAD | QRP | MITS | QUAD | QRP | MITS | QUAD |
| Responsive § | 100 | 0.40 | 0.25 | 0.26 | 52 | 44 | 104 | 0.64 | 0.60 | 0.43 |
| | 200 | 0.48 | 0.35 | 0.15 | 47 | 51 | 156 | 0.84 | 0.96 | 0.36 |
| | 400 | 0.49 | 0.39 | 0.30 | 44 | 58 | 161 | 0.95 | 1.31 | 0.43 |
| All 70 ‡ | 100 | 0.23 | 0.23 | 0.25 | 71 | 63 | 90 | 0.50 | 0.50 | 0.51 |
| | 200 | 0.17 | 0.25 | 0.19 | 92 | 94 | 145 | 0.53 | 0.69 | 0.42 |
| | 400 | 0.16 | 0.24 | 0.07 | 105 | 126 | 196 | 0.55 | 0.88 | 0.26 |

§ : Sites were included in the analysis only if fit of the model was statistically significant at $p = 0.05$.

‡: Two sites having economic optimum rates greater than 400 kg/ha were excluded.

A noteworthy point of disagreement is revealed by the intercept values for linear relationships fit to data in Fig. 5 (see Table 3). Each of the models based on yield response called for substantial amounts of fertilizer where the models based on response of the YB index called for none. Evidence that the YB index method is more reliable in this region is provided in Fig. 3, which shows clear superiority of the YB index method where yield responses are small.

The quadratic model gave highly questionable estimates of optimal rates of fertilization at prices favorable for producers because it indicated that sites should receive either nothing or relatively high rates of N (Fig. 5). This result can be explained by recognizing that this model always assumes that yield increases at below-optimal rate are symmetrical with yield decreases in the above-optimal range. This model, therefore, should not be expected to provide reasonable estimates of optimal N rates where yields plateau at above-optimal rates of fertilization.

The MITS model assumes that yields should asymptotically approach a maximum as yields are increased. This model, therefore, is not appropriate where yields show a tendency to decrease with above-optimal rates of fertilization. Moreover, slope of the model at near-optimal rates of fertilization is greatly influenced by yields observed with extreme deficiencies. Unwanted effects of data collected from plots with extreme deficiencies is difficult to avoid because poor predictability and statistically insignificant relationships become a problem unless plots with extreme deficiencies are included in the analysis.

The QRP model cannot be used to describe yield responses unless numerous rates of N are included in the trial. When yield responses are small, there often is a problem identifying the N rate and yields at which the two segments of the model should converge.

As with the MITS model, therefore, poor predictability and statistically insignificant relationships are a problem unless data from plots with extreme deficiencies are included in the analysis. When such data are included, determinations of optimal rates of fertilization are biased by information not relevant to the exact shape of the response curve near optimal rates of N fertilization. Such bias could cause the type of disagreements among models observed in this paper and this problem would be difficult to solve by merely comparing alternative models based on yield response.

## Conclusions

Observations made in this study reveal an unavoidable dilemma associated with using yield response measurements to identify optimal rates of fertilization; an investigator must choose between working with poor relationships or giving much weight to observations made under conditions of extreme deficiency. This dilemma occurs because yield responses are indirect indicators of N sufficiency and because statistically significant trends can be attained only when rates of fertilization are below optimal. Conclusions about optimal rates of fertilization are largely based on lack of significant response, or negative evidence. Lack of statistically significant response is not very convincing because field studies tend to have much less sensitivity than desired. The severity of this limitation is illustrated in Fig. 3, which shows that yield response measurements cannot be used to identify optimal rates of N fertilization unless yield responses are greater than 1 Mg/ha. Methods offering greater sensitivity could substantially aid efforts to optimize N management in production systems where high levels of nutrient availability are maintained.

This dilemma can be avoided by using YB index values to characterize plant responses to fertilizer because the YB index is a direct measure of N sufficiency that tends to increase linearly with rates of fertilization throughout the range of practical interest. The relative distance of any YB index value from optimal YB index values can be calculated easily. Statistically significant trends can be measured even when all data are collected from sites having optimal and above optimal rates of N application. Given the great economic and environmental importance of selecting optimal rates of N fertilization in modern production systems, the potential of using YB index values for identifying optimal rates of N fertilization needs to be more fully explored.

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# REFINED INTERPRETATIONS FOR THE END-OF-SEASON TEST FOR CORNSTALK NITRATE

A paper to be submitted to the Agronomy Journal

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## Abstract

The end-of-season test for cornstalk nitrate has been used to evaluate and improve nitrogen management during corn (*Zea mays* L.) production. Use of the test, however, is limited by guidelines that are more qualitative than quantitative. Data from 70 non-manured response trials with seven or more N treatments were analyzed to develop guidelines that define end-of-season cornstalk nitrate categories in terms of mean net returns and probabilities of a profitable yield response to fertilizer-N across the range of prices for corn and fertilizer commonly found in production agriculture. At sites testing in the low cornstalk nitrate category, probabilities of positive net returns to 112 kg /ha fertilizer N varied from 79% to 95%, and mean net returns ranged from 1.08 to 1.92 Mg grain/ha when the price ratio of corn to fertilizer N varied from 100 to 400 (kg N/Mg grain). In contrast, sites testing in the above-optimal category had positive return probabilities of 0%, and mean net returns varied from –1.69 to –0.85 Mg grain/ha when the same N rate and price ratios were applied. Relationships also were developed that relate cornstalk nitrate concentrations to additional quantities of fertilizer N that should have been applied. Results show that the end-of-season test for cornstalk nitrate is a useful tool to evaluate N management.

## Introduction

Concentrations of nitrate in cornstalks at the end of the season provide the basis for a tissue test that can be used to make after-the-fact assessments of N sufficiency for corn growth

(Binford et al. 1990, 1992; Sims et al, 1995; Varvel et al, 1997). This test is unique among tissue tests for corn in that it characterizes degrees of N excess as well as degrees of N deficiencies. The test can be used to help interpret results of N-response studies (Binford et al., 1992; Morris et al, 1993; Blackmer and White, 1998) or to evaluate and improve N management practices in production agriculture (El-Hout and Blackmer,1990; Balkcom and Blackmer, 1999). Current guidelines for using this test in Iowa (Blackmer and Mallarino, 1996) recommend that corn producers take a few samples from each of their fields to evaluate their N management and thereby obtain site-specific feedback that can be used to improve their management.

Current interpretations of the stalk test in Iowa (Blackmer and Mallarino, 1996) divide cornstalk nitrate concentrations into four categories: low, 0 to 250 mg N/kg; marginal, 250 to 700 mg N/kg; optimal, 700 to 2000 mg N/kg; and above optimal, >2000 mg N/kg. Low concentrations are interpreted to indicate high probability that greater availability of N would have resulted in higher yields. Marginal concentrations, while indicative of a high probability that N availability was in the range needed to maximize profits, are considered to be "too close" to low to serve as a target concentration. Optimal concentrations are interpreted to indicate high probability that N availability was in the range needed to maximize profits for producers. Above-optimal concentrations indicate high probably that N availability was greater than if fertilizer N had been applied at rates that maximized profits for producers.

Here we describe efforts to refine interpretations of the stalk test by developing recommendations concerning how rates of fertilization should be changed when various stalk nitrate concentrations are observed in fields fertilized by farmers. We reason that the task of developing such recommendations is clearly different from the task of assessing total fertilizer needs for a crop. Unlike estimates of fertilizer requirement, deviations of rates from optimal can be either positive or negative. Deviations from optimal should tend to be much smaller than the total amount of fertilizer required. Recommendations concerning total fertilizer needs and recommendations for changes in rates, however, are similar in that both must be based on observations made in the past.

The task of refining interpretations for the end-of-season test for cornstalk nitrate seems to have been simplified by recent development of the YB index (Part one of this dissertation). Although YB index values are calculated directly from stalk nitrate concentrations, they differ from cornstalk nitrate concentrations because they tend to form linear relationships with amounts of fertilizer N applied in response trials. Analyses presented in Part 2 of this dissertation show that YB index values tend to be linearly related to rates of fertilization through the range of N-sufficiency levels of interest when identifying optimal rates of N fertilization. Because optimal YB indices also were established, these linear relationships should be helpful when trying to estimate how much a rate of fertilization deviates from optimal.

## Materials and Methods

Data were taken from a total of 1813 plots from 70 N-response trials conducted in Iowa over a period of six years (1986 - 1991). Most of the response trials are described by Davis (1992), Binford et al. (1992), and Meese (1993). Each trial involved application of at least six rates of N to replicated and randomized plots before corn was planted. Fertilizer N was applied in the form of urea, ammonium nitrate or anhydrous ammonia in either late fall of the previous year or the early spring. Preceding crops were corn or soybean. Measurements taken from each trial included concentrations of nitrate in the soil in late spring and in corn stalks at harvest.

Cornstalk samples were collected from 7.6-m sections of the center two rows of each plot. Each sample consisted of sixteen 20-cm sections of the plant taken from 16 to 36-cm above the ground. Air-dried cornstalk samples were ground to pass a 2.0-mm sieve. A 0.5- to 1.0-g sample of the ground cornstalk is extracted with 50 ml of 0.025 M $Al_2(SO_4)_3$. The filtered extracts were treated with 1 ml of 2 $(NH_4)_2SO_4$ to each 50-ml extract to minimize differences in ionic strength. Nitrate determinations of the prepared extracts were performed using an Orion Model 93-07 nitrate specific electrode (Orion Research Inc., Boston MA).

Mean net returns (Mg/ha) to N fertilization for each site and N increment were calculated for various price ratios by subtracting the cost of fertilizer and fertilizer application (expressed as a quantity of grain) from the quantity of grain produced on fertilized plots compared with plots that did not receive the additional N or received less fertilizer N by the given amount. An application cost of 0.1 Mg of grain was assumed. The price scenarios were selected to include the range of prices found in Iowa (N.A.S.S., 1999).

Transformation of cornstalk nitrate concentrations to YB indices is given by Equation [1] (Yang and Blackmer,1997). This transformation gives an index of nitrogen sufficiency that is linearly related to availability of N for corn growth. This index has negative values when availability of N is below optimal and positive values when availability of N is above optimal.

$$\text{YB Index} = 11.43-100*\log_{10}(\log_{10}(14{,}000/\text{stalk\_nitrate})) \qquad [1]$$

Cornstalk nitrate categories used were based on those presented by Blackmer and Mallarino (1996). Least significant difference (LSD) values for yield responses for pooled data were calculated after Snedecor and Cochran (1980). The treatment effect required by this method was determined by standard analysis of variance (ANOVA) techniques.

Results

Yield responses to N fertilization showed a statistically significant trend to increase with decreasing stalk nitrate concentrations on control plots (Fig. 1). This trend should be expected because the stalk test indicates the N sufficiency level without added N and because sufficiency level of N is a major factor affecting yield responses to N. The relatively low $r^2$ values at the lowest rate of fertilization is consistent with observations that small yield responses are difficult to measure amid normal unexplained variations in yield within response trials. It was shown in paper 2 of this dissertation, for example, that it is difficult to detect yield responses less than 1 Mg/ha. The models presented in Fig. 1 estimate the effects of initial N sufficiency level on yield response to N.

Figure 2 shows relationships between yield responses and YB index values, which are alternative measures of N sufficiency level. The transformation redistributes points along the x-axis by placing more space between points at lower sufficiency levels and less space between points at sufficiency levels. The position of points on the y-axis is not changed. Although the transformation alters coefficients in models fit to the data, it has no effect on $r^2$ values or the extent to which observations differ from the model. The primary advantage of this transformation is that, unlike stalk nitrate concentrations, YB index values are linearly related to amounts of fertilizer applied (Part 2 of this dissertation). Such linear relationships

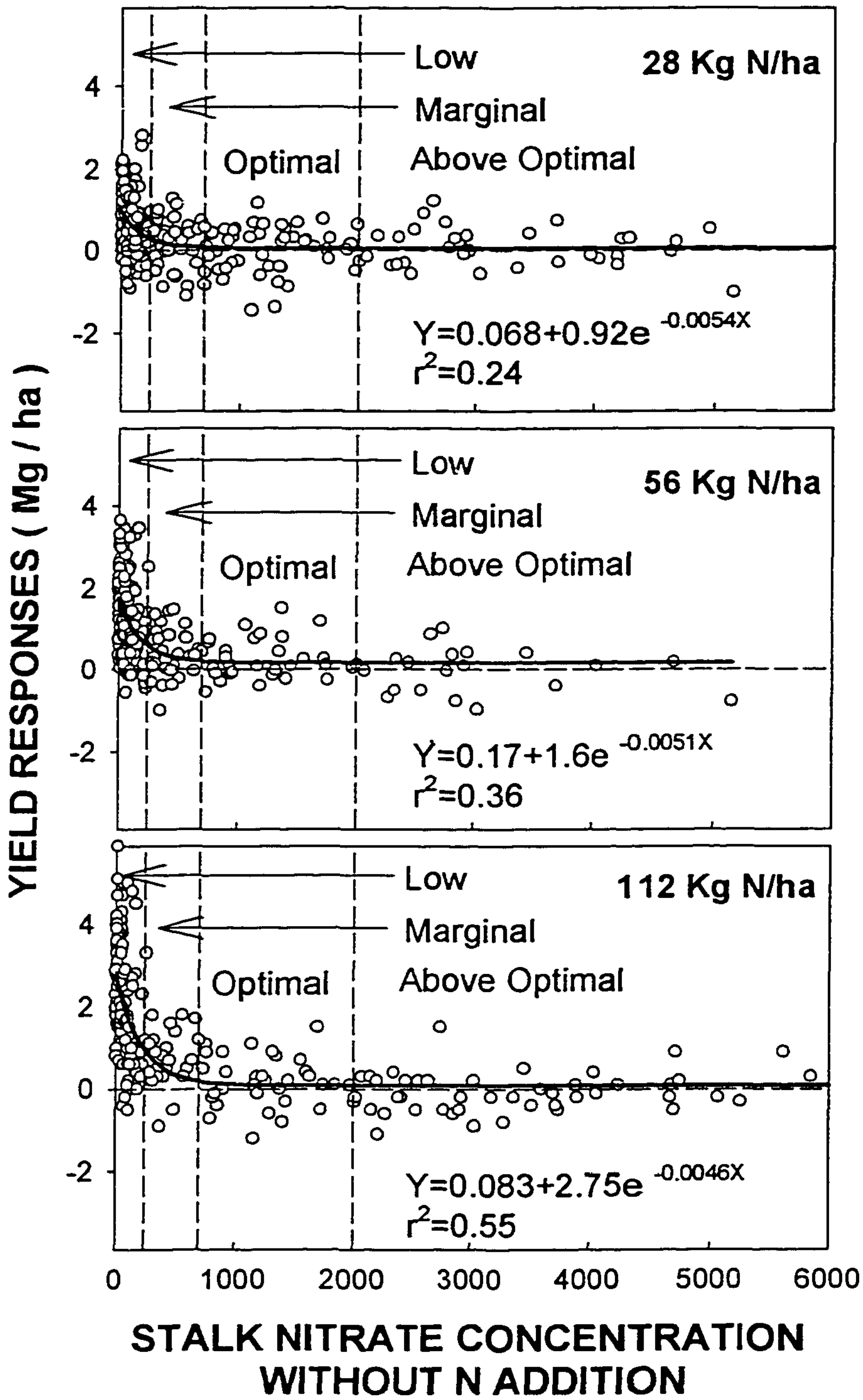


Figure 1. Relationship between stalk nitrate concentration and corn yield responses to 28, 56, and 112 kg N /ha.

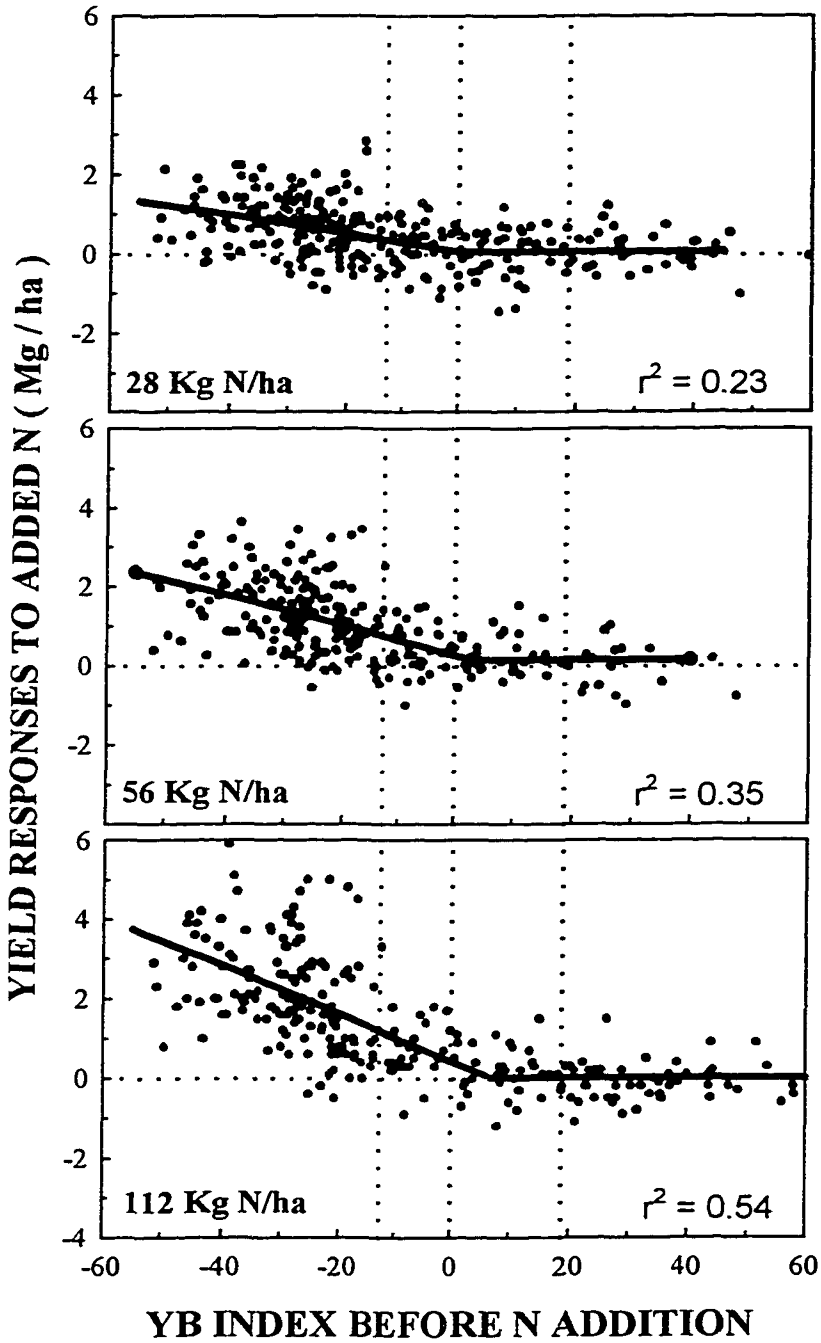


Figure 2. Relationship between YB index values and corn response to 28, 56, and 112 kg N/ha added N.

greatly simplify the task of using the stalk test to evaluate and improve N management practices.

Table 1 shows the mean increases in yields for various categories formed by considering initial N sufficiency level and rates of N fertilization. Mean increases in yield ranged from –0.47 to 2.30 Mg/ha for various categories. We have no explanation for the observation that mean yields decreased when 56 and 112 kg N/ha were applied at sites where stalks on the control plots had above-optimal concentrations of stalk nitrate. This observation, however, is statistically significant and important when estimating the costs associated with applying too much or too little N.

The percentage of sites showing positive yield responses varied greatly among categories formed by considering rates of fertilization and stalk nitrate concentrations on control plots (Table 2). Mean percentages of sites showing increases for the various categories ranged from 48 to 98%, which means that yield decreases to added N ranged from 2 to 52% of the sites within the categories. Of the group of sites that have cornstalk nitrate concentrations greater than 2000 mg N/kg in the control plots, the number of sites showing a positive response to added N was approximately equal to the number of sites having a negative response.

Table 3 shows percentages of sites within various categories where fertilization resulted in a profit. The categories consider grain-to-fertilizer price ratios as well as rate of N fertilization and N-sufficiency level of the control. The price conditions considered range from relatively unfavorable to relatively favorable for producers based on prices for grain and fertilizer found in the Corn Belt during the past decade. The percentages shown tend to be considerably lower than those presented in Table 2 because costs of fertilization are considered. Because fertilizers are applied to increase profits, the information presented in Table 3 is much more useful than the information presented in Table 2. Recognizing the difference between yield responses and profits is important when making fertilizer recommendations.

Table 4 shows mean net returns to fertilization for various categories formed by considering grain-to-fertilizer price ratios, rate of N fertilization, and initial N-sufficiency level. Net returns to fertilization is expressed in units of Mg grain/ha to avoid the need to restrict interpretations to exact prices, but net returns to fertilization in $/ha can be calculated

Table 1. Mean yield response to added N when plots are grouped by nitrate concentration in cornstalks and by rates of fertilization.

| Stalk N category | Mean yield response to various quantity of added N | | |
|---|---|---|---|
| | 28 kg/ha | 56 kg/ha | 112 kg/ha |
| mgN/kg | | Mg/ha | |
| <250 | 0.72(0.05) ξ | 1.34(0.07) | 2.30(0.12) |
| 250-700 | 0.15(0.10) | 0.44(0.12) | 0.96(0.19) |
| 700-2000 | 0.13(0.09) | 0.26(0.09) | 0.40(0.21) |
| >2000 | 0.12(0.09) | -0.03(0.12) | -0.47(0.12) |

ξ: Numbers in parentheses are standard error of the means.

Table 2. Probability of positive yield response to added N when plots are grouped by nitrate concentrations in cornstalks from plots that did not receive the added increment of N.

| Stalk N category | Probability of positive response to various quantity of added N | | |
|---|---|---|---|
| | 28 kg/ha | 56 kg/ha | 112 kg/ha |
| mgN/kg | | % | |
| <250 | 85(159/186) ξ | 92(98/107) | 98(60/61) |
| 250-700 | 64(28/44) | 85(28/33) | 85(17/20) |
| 700-2000 | 63(32/51) | 58(32/55) | 58(14/24) |
| >2000 | 53(19/36) | 50(63/126) | 48(25/52) |

ξ: Numbers in the parentheses are the number of sites showing positive yield responses and the total number of sites in the category.

Table 3. Probability of positive net returns to added N calculated for 5 price ratios when plots are grouped by nitrate concentration in cornstalks and by rates of fertilization.

| Stalk N | | Percentage of positive net returns to added N | | | | |
|---|---|---|---|---|---|---|
| category | N rate | 100 | 150 | 200 | 300 | 400 |
| mgN/kg | kg N/ha | | | % | | |
| <250 | 28 | 70 | 74 | 77 | 78 | 79 |
| | 56 | 76 | 80 | 84 | 87 | 90 |
| | 112 | 79 | 85 | 88 | 93 | 95 |
| 250-700 | 28 | 43 | 48 | 50 | 52 | 52 |
| | 56 | 37 | 39 | 45 | 55 | 61 |
| | 112 | 18 | 47 | 53 | 65 | 82 |
| 700-2000 | 28 | 33 | 43 | 51 | 53 | 55 |
| | 56 | 27 | 27 | 33 | 37 | 43 |
| | 112 | 8 | 33 | 50 | 50 | 58 |
| >2000 | 28 | 22 | 39 | 42 | 47 | 47 |
| | 56 | 10 | 10 | 20 | 25 | 30 |
| | 112 | 0 | 0 | 0 | 0 | 0 |

Price ratios equal to the price of corn in $/Mg divided by the cost of N in $/kg.
Mean net returns are calculated by subtracting the N rate divided by price ratio from the mean yield response (Mean yield response - N rate /price ratio - 0.1 Mg/ha application cost).

easily by using any appropriate price for grain. These means provide the best available estimates of the profit or loss that could be expected from fertilization under conditions reasonably similar to those included in this study.

Three important findings are presented in Table 4. First, mean net returns to fertilization were negative for all categories where stalks on the control plots tested in or above the optimal range. Second, mean net returns were positive for all categories where stalks from the control plots tested in the low range. And third, mean net returns to fertilization changed from negative to positive for those sites where stalk nitrate in the control plots tested in the marginal category as price ratios increased. These observations support current interpretations of the stalk test.

Table 4. Mean net returns to added N calculated for 5 price ratios when plots are grouped by nitrate concentration in cornstalks from plots that did not receive the added increment of N

| Stalk N category | N rate | Mean net returns to added N at various price ratios 100 | 150 | 200 | 300 | 400 |
|---|---|---|---|---|---|---|
| mgN/kg | kg N/ha | ------------------- | | Mg/ha | -------------------------- | |
| <250 | 28 | 0.34 | 0.43 | 0.48 | 0.53 | 0.55 |
| | 56 | 0.56 | 0.75 | 0.84 | 0.93 | 0.98 |
| | 112 | 1.01 | 1.38 | 1.57 | 1.76 | 1.85 |
| 250-700 | 28 | -0.23 | -0.14 | -0.09 | -0.04 | -0.02 |
| | 56 | -0.14 | 0.05 | 0.14 | 0.23 | 0.28 |
| | 112 | -0.64 | -0.27 | -0.08 | 0.11 | 0.20 |
| 700-2000 | 28 | -0.25 | -0.16 | -0.11 | -0.06 | -0.04 |
| | 56 | -0.50 | -0.31 | -0.22 | -0.13 | -0.08 |
| | 112 | -1.18 | -0.81 | -0.62 | -0.43 | -0.34 |
| >2000 | 28 | -0.26 | -0.17 | -0.12 | -0.07 | -0.05 |
| | 56 | -0.67 | -0.48 | -0.39 | -0.30 | -0.25 |
| | 112 | -1.20 | -0.83 | -0.64 | -0.45 | -0.36 |

Price ratios equal to the price of corn in \$/Mg divided by the cost of N in \$/kg.
Mean net returns are calculated by subtracting the N rate divided by price ratio from the mean yield response (Mean yield response - N rate /price ratio - 0.1 Mg/ha application cost).

Figure 3 illustrates the ranges of N sufficiency level over which various rates of N fertilization tended to maximize profits within each of the three price scenarios. The solid lines in Fig. 3 are models fit to the data similar to those in Fig. 2 except that the Y axis showed net returns to fertilization in Fig. 3 rather than yield responses. Data points are not presented because they appear identical to those in Fig. 2 except the numbers and words shown on the Y-axis differ.

Vertical dotted lines in Fig 3 show the initial N-sufficiency levels at which two rates of N gave equal net returns to fertilization within a price scenario. We denote these as "breakpoint sufficiency levels" and note that they have similarity to "critical levels", which are often used to distinguish between sites where fertilizer should be applied from sites where fertilizer N should not be applied. A key difference is that breakpoint sufficiency levels are used to specify rates whereas critical concentrations usually do not address the rate of fertilization needed.

Figures 2 and 3 are referenced to the initial N sufficiency levels of N at a site and provide information that can be used to estimate likely benefits of applying more N than was actually applied to a site. When stalk test values are high, however, the likely benefits of adding less N are also of interest. Such information is better obtained from analyses referenced to N sufficiency levels attained by fertilization as shown in Fig.4. Data presented in Fig. 4 show that reducing N application rate by 112 kg N/ha, for example, would not have changed yields in situations where YB index values exceeded 40.

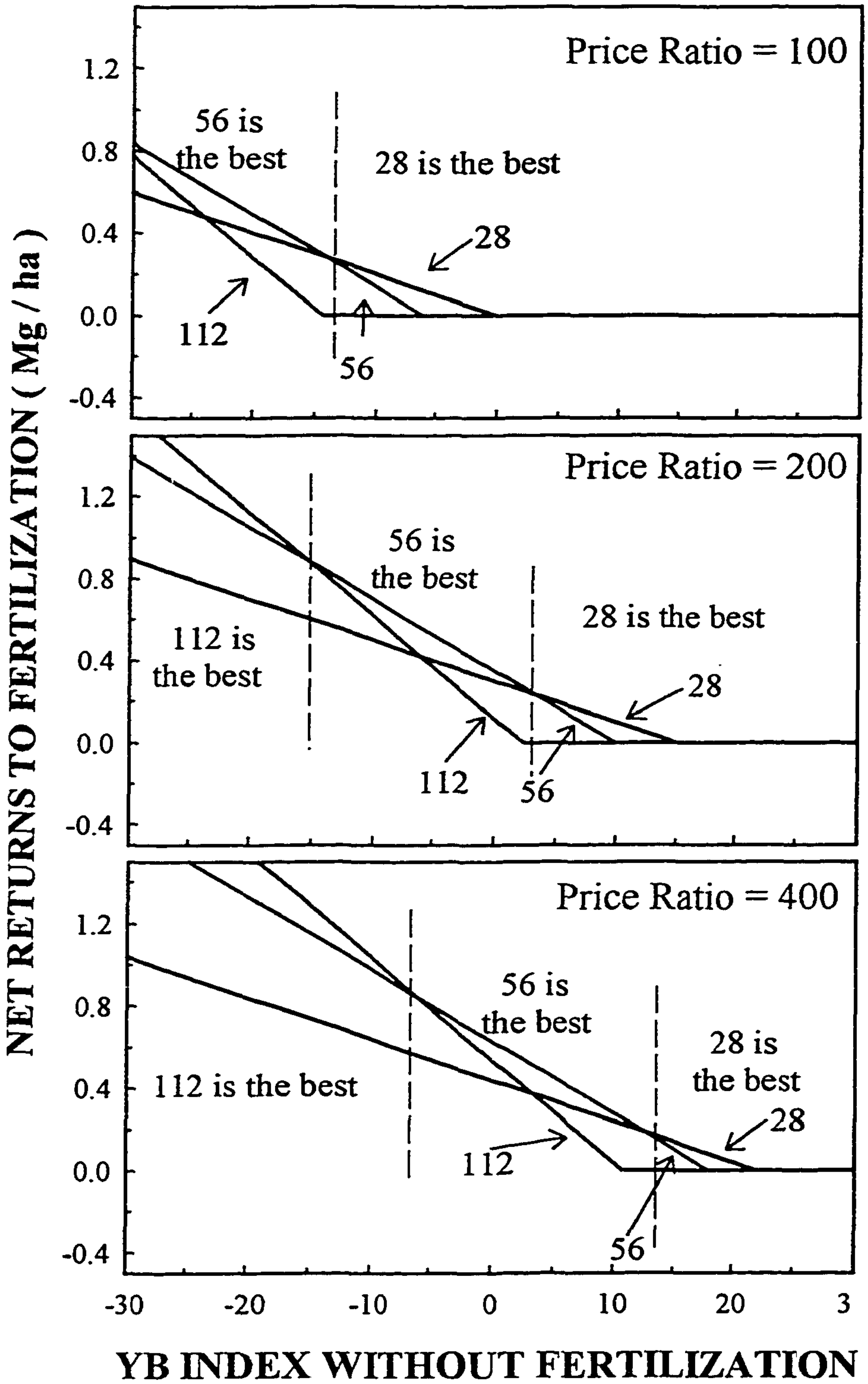


Figure 3. Best fertilization rates with respect to the YB index values of the control plots under different price scenarios.

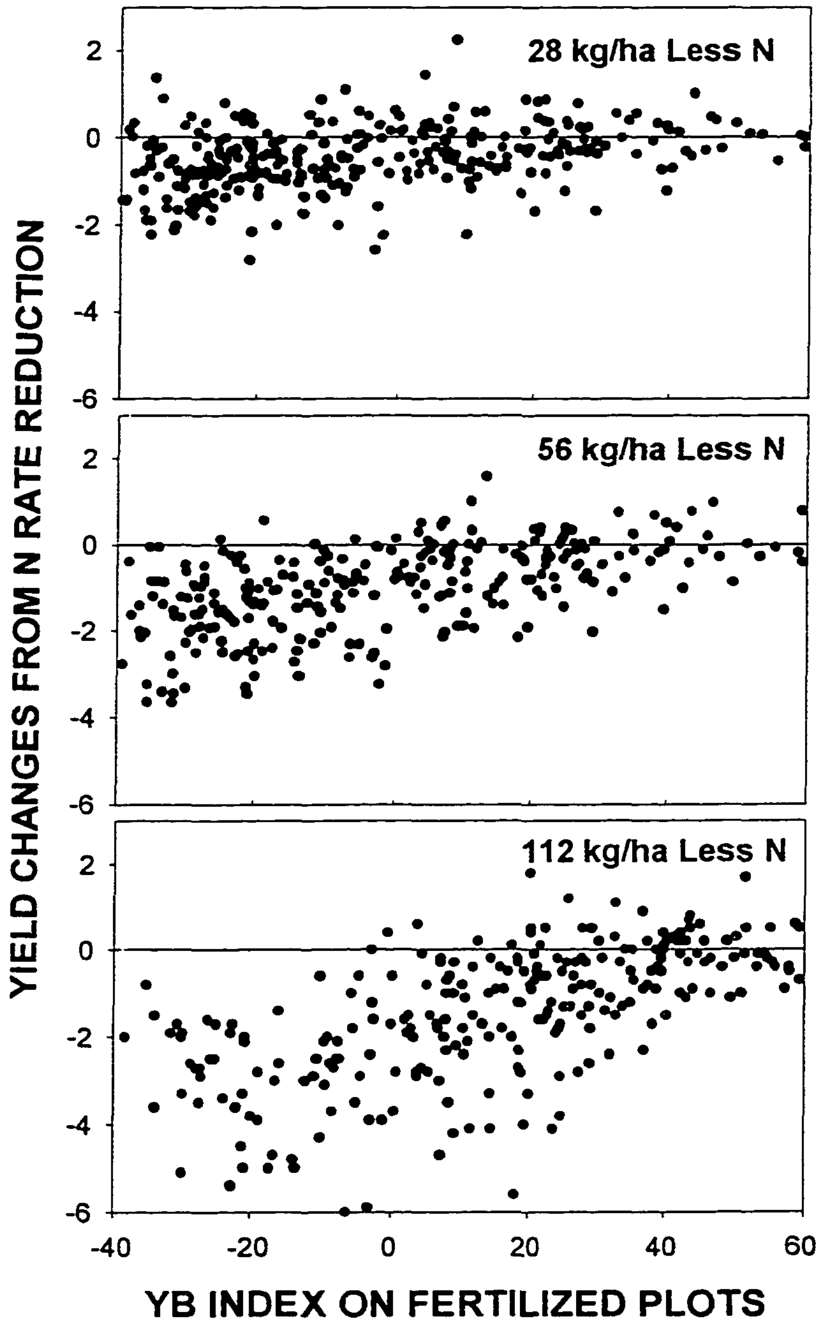


Figure 4. Effects of the YB index values on changes of yields if N rates had been reduced by 28, 56, and 112 kg N/ha. Notice that if the site had YB index values of greater than 40, reducing N rates by 56 and 112 kg N/ha would have resulted in NO significant yield loss.

Figure 5 illustrates the ranges of YB index values over which reductions in rates of fertilization by various amounts would have maximized profits across all sites under different price conditions. The vertical dotted lines show the breakpoint YB index values, where two different rates of reduction would have resulted in the same benefit.

Figure 6 shows relationships between fertilizer-to-grain price ratios and breakpoint YB index values for various rates of N fertilization, and it provides information needed for the interpretation of end-of-season stalk nitrate test. The points in this figure are the breakpoint sufficiency levels that could be derived from a series of figures like 3 and 5 for different price ratios. Fig. 6 can be used to interpret the results of any given stalk nitrate test for any given price condition. Based on observations made in this study, for example, the finding of a YB index value of 30 at a price ratio of 200 can be interpreted by concluding that profits probably would have been maximized if about 28 kg N/ha less fertilizer had applied than was applied.

## Discussion

The interpretations developed in this report are based on average responses to fertilization observed across many trials rather than responses observed at the site and year where the sample was collected. Such interpretations clearly would not be desirable if the stalk test is being used to help explain yield responses or other data collected within yield response trials. Such interpretations are desirable, however, when results of the stalk test are being used to assess N sufficiency in fertilized fields with the objective of adjusting rates of fertilization toward optimal. Because N responses are influenced by many factors other than rates of N application, the mean of many observations made across reasonably similar conditions provides a better estimate of the expected benefits of changing rates than do

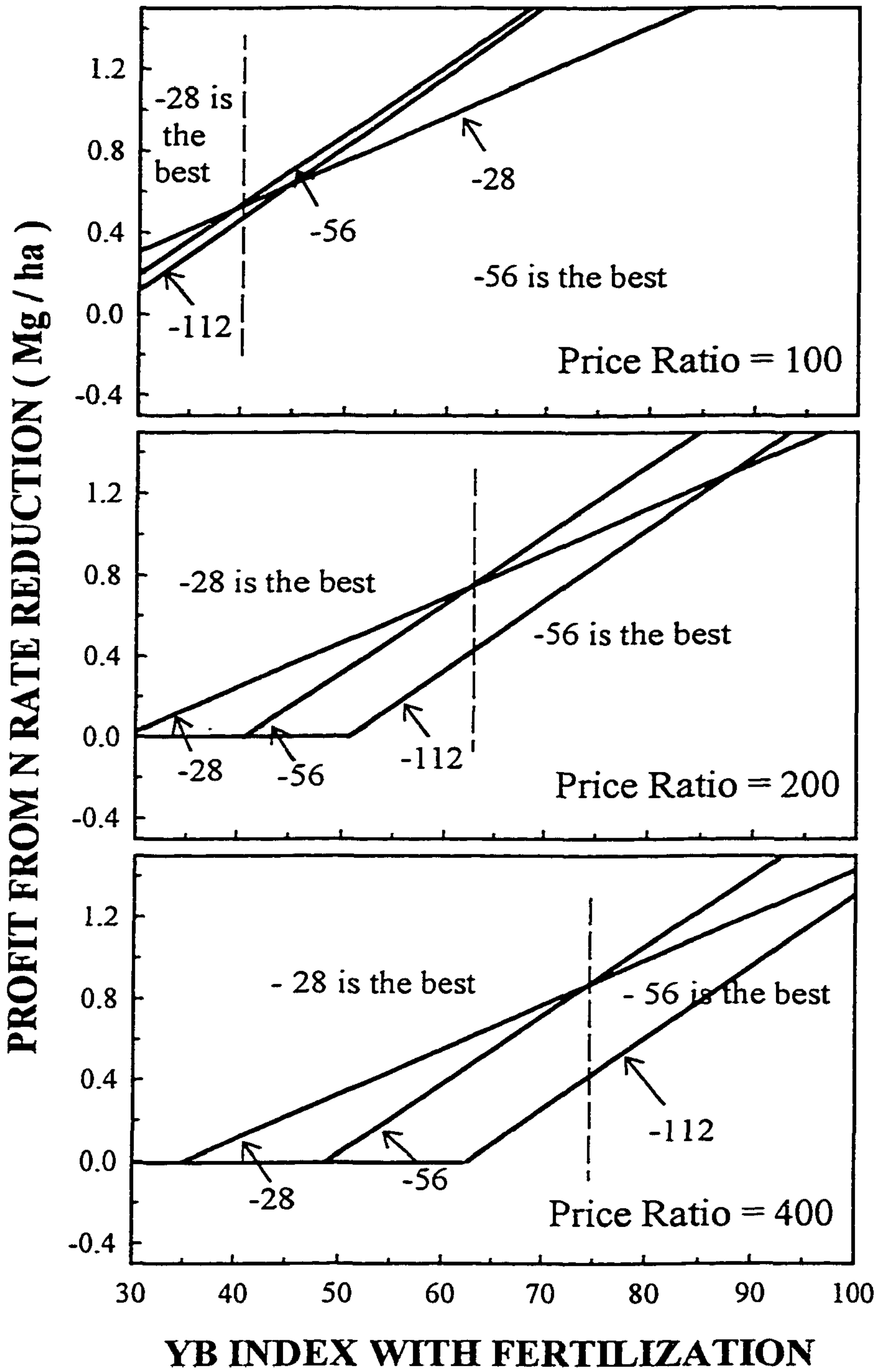


Figure 5. Calculated profits from N rate reductions by 28, 56, and 112 kg N/ha with respect to the YB index values of the plots to which fertilizer N was added. Vertical dotted lines denote the breakpoint YB index values where two different rates of reduction would result in the same profit.

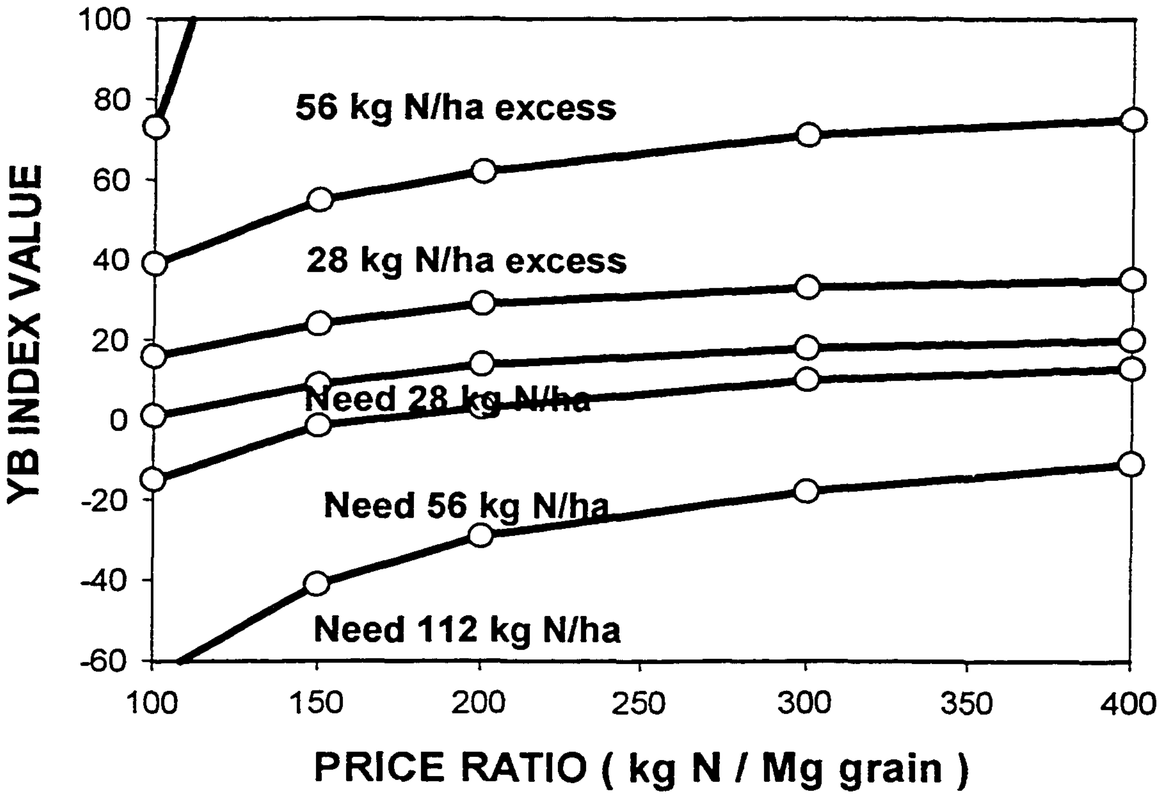


Figure 6. Breakpoint YB index values and the price ratio of grain to fertilizer N. This diagram can be used to interpret the results of end-of-season stalk nitrate test, and it provides information needed to evaluate the N management practices.

observations made at a single year.

Interpretations that include estimates of the probabilities that greater profits would have been attained with higher or lower rates of fertilization give clear assessments of the uncertainty associated with any recommendation. Estimating these probabilities within categories formed by considering N-sufficiency levels and rates of fertilization avoids confusion concerning where uncertainty is important and where it is not. Data in Table 3, for example, clearly indicate that high levels of uncertainty at near-optimal levels of N sufficiency should not be extrapolated to conditions where N-sufficiency levels were relatively high or low.

Uncertainty as to whether profits would be increased or decreased by small changes in rates at near-optimal sufficiency levels within given price conditions is relatively unimportant because expected changes in profits are relatively small. Within this range, the importance of small changes in rates is diminished by the tendency for yields to change and partially offset differences in costs of fertilization. Data presented in Table 4 (and Fig. 1) indicate that benefits of changing fertilization rate by 28 kg N/ha are essentially undetectable within this range. However, the effects of changing rates of fertilization by 28 kg N/ha are detectable and important when N-sufficiency levels are far above or below optimal.

Estimated benefits from small changes in rates of fertilization at near-optimal levels of N sufficiency level vary with price conditions. Because price conditions vary substantially with time and location, it is important the expected benefits of changes in fertilization rates are estimated by using appropriate prices. The fact that some uncertainty in prices often exists when fertilizers must be applied only slightly diminishes the importance of considering prices. Use of Fig. 6 makes it easy to consider the effects of prices when using the stalk test to recommend how rates of fertilization should be changed.

Small changes in rates of fertilization at near-optimal levels of N sufficiency does not substantially diminish the problems associated with estimating optimal rates of fertilization from yield response trials. Disagreements between models are often quite large (see Table 1 of paper 2 in this dissertation) and these disagreements occur due to effects observed at sufficiency levels far above and below optimal. This finding, however, gives support to the idea of estimating benefits of fertilization only at rates actually applied in experiments and interpolating between rates when making the final interpretation. Grouping soils by sufficiency level before benefits are calculated avoids the problem of confusing the expected benefits of fertilization within the optimal range with effects of fertilization above or below this range.

This paper does not address important questions relating to the range of conditions over which the interpretations should be used. It should not be assumed that the interpretations developed here apply to conditions that differ greatly from those reported here, and they should not be used in situations where stalk nitrate concentrations were greatly influenced by unusual weather, soil conditions, or management practices. The range over which interpretations are useful can be assessed only through other studies under other conditions. However, devising a method for developing interpretations and an initial set of interpretations is an essential first step in exploring the range over which the interpretations are useful.

Discussions that focus on finding ways to improve interpretations of the stalk test should not be allowed to overshadow evidence that precise interpretations of the stalk test often are not needed to evaluate and improve N management. Surveys of cornfields in Iowa indicate that a high percentage of fields do not have near-optimal levels of N sufficiency and, therefore, that highly precise interpretations of the test often are not needed to substantially improve N management (El-Hout and Blackmer, 1990; Balkcom and Blackmer, 1999). The same surveys, however, indicate that many producers are managing N well enough that refinements in interpretations would be very useful.

## Conclusions

It is possible to refine interpretations for the end-of-season test for cornstalk nitrate to evaluate and improve N management in production agriculture. Data collected in N-response trials across many sites and years can be used to estimate likely benefits of increasing or decreasing rates of fertilization. Such data can be used to estimate the probability of obtaining a benefit from a given change in rate and estimate the average benefit that can be expected. Because the stalk test indicates N-sufficiency level in the crop sampled, site-specific assessments of existing N-sufficiency levels can be used when estimating the benefits of changing rates. This minimizes the problem of confusing the benefits of changing rates of fertilization at near-optimal sufficiency levels with the benefits of changing rates at N-sufficiency levels that are significantly above or below optimal.

The expected benefits of changing rates of fertilization can be expressed in terms of expected profits for producer by considering the effects of grain-to-fertilizer price ratios. The probability of obtaining a profit and the average profit expected can be calculated for given changes in rate of fertilization at specified N-sufficiency levels and prices. Recommendations for changes in rates of fertilization based on observed stalk nitrate concentrations and existing price conditions can be easily read from a figure. Although existing interpretations for the test are adequate to evaluate and improve N management under many conditions, ongoing efforts to refine interpretations of the stalk test are needed where prevailing N management practices usually result in near-optimal levels of N sufficiency in crops.

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# GENERAL CONCLUSION

Data from 70 trials conducted in Iowa from 1986 to 1991 were pooled together for analysis of the relationships among soil test values, yields, and stalk nitrate concentrations at the end of the season. The objectives of these studies were to i) characterize the relationships between the results of end-of-season stalk test and the late-spring soil test values, ii) use stalk nitrate concentrations to determine the economic rates of fertilization, and iii) develop quantitative guidelines for the use of the end-of-season test for cornstalk nitrate in non-manured soils.

Results in "development of the YB index of nitrogen sufficiency in corn" showed that the relationship between soil test values and the results of stalk nitrate test was not linear. A nitrogen index, the YB index, was developed to linearize this relationship. This index is calculated by the formula -100Log(Log(14000/StalkN)) + 11.4, where StalkN denotes concentrations of stalk nitrate in mg N/kg. The index has a value of zero at the stalk nitrate concentration judged to be optimal (700 mg N/kg), positive values at higher concentrations, and negative values at lower concentrations. YB index provides a measure of N sufficiency level and is very easy to use in evaluating N management practices. The YB index should be especially useful in studies where too few rates are applied to use discontinuous models. Because effective studies can be conducted when only a few rates of N are applied in the near-optimal range, use of the YB index offers the possibility of greatly increasing experimental efficiency in studies designed to fine-tune existing recommendations.

Results in "use of the YB index to identify optimal rates of nitrogen fertilization for corn" showed that there is an unavoidable dilemma associated with using yield response measurements to identify optimal rates of fertilization; one must choose between working with poor relationships or giving much weight to observations made under conditions of extreme deficiency. This dilemma occurs because yield responses are indirect indicators of N sufficiency and because statistically significant trends can be attained only when rates of fertilization are below optimal. Conclusions about optimal rates of fertilization are largely based on lack of significant response, or negative evidence. Lack of statistically significant response is not very convincing because field studies tend to have much less sensitivity than desired. It was illustrated that yield response measurements cannot be used to identify optimal rates of N fertilization unless yield responses are greater than 1 Mg/ha. Methods offering greater sensitivity could substantially aid efforts to optimize N management in production systems where high levels of nutrient availability are maintained.

The dilemma could be avoided by using YB index values to characterize plant responses to fertilizer because the YB index is a direct measure of N sufficiency that tends to increase linearly with rates of fertilization throughout the range of practical interest. The relative distance of any YB index value from the optimal YB index values can be calculated easily. Statistically significant trends can be measured even when all data are collected from sites having optimal and above optimal rates of N application. Given the great economic and environmental importance of selecting optimal rates of N fertilization in modern production systems, the potential of using YB index values for identifying optimal rates of N fertilization needs to be more fully explored.

"Refined interpretations for the end-of-season test for cornstalk nitrate" showed that YB index values could be used for refined interpretations of the results from the end-of-season stalk nitrate test. YB index values could be used to give feedback to farmers on how much more or less fertilizer N should have been applied to their fields under the growing conditions and the given price scenario. This after-the-fact evaluation is important for farmers to become better in managing nitrogen fertilization in their fields in the future.

Overall, the results of these studies indicated that there was a nonlinear relationship between the nitrate concentrations from the end-of-season stalk test and the nitrate concentrations from the late spring soil test and this relationship was linearized by the YB index transformation, that YB index values could be used for quantative analysis of profit maximizing fertilization rates, and that the cornstalk nitrate test and the late-spring soil test could be used to provide site specific information for improving N fertilizer recommendations for today's precision farming.

## ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my major advisor, Dr. Alfred Blackmer, for making it possible for me to complete a Master's degree in Agronomy, and then pursue concurrently a Master's degree in Computer Science and a Doctor of Philosopher degree in Agronomy at Iowa State University through a research assistantship. I am also indebted to him for his expertise, invaluable guidance, and encouragement during my entire graduate program. Sincere appreciation is extended to Drs. Leslie Miller, Robert Horton, Antonio Mallarino, and William Batchelor for their advice and time spent serving on my graduate committee.

Thanks are due to my fellow graduate students for their friendships: Kim C. Chin, Dave Hansen, Jason Ellsworth, Kip Balcom, Jun Zhang, and Susan White.

Special thanks go to my wife, Yinhua Li, for her considerable encouragement, support, and patience during this endeavor. I would also like to thank my parents for their support.